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REFERENCE

Lane, B. H., 1935. Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C., 25c.)

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THE PEGMATITE LAYER IN THE SHONKIN SAG LACCOLITH, MONTANA

JULIAN D. BARKSDALE

ABSTRACT. A re-examination of the Shonkin Sag laccolith and the associated intrusions in Montana is the basis for the conclusion that the layering in the laccolith is due to differentiation in place from a single intrusion. New data on the pegmatite layer, unique to the Shonkin Sag laccolith, are presented and three hypotheses of the origin of the layer are discussed.

INTRODUCTION

THE Shonkin Sag laccolith was first mentioned by Weed and Pirsson (1895, p. 399). In a later paper Pirsson (1905, pp. 183-190) explained the prominent layering that characterizes the intrusion as having been caused by a combination of crystallization and convection. Osborne and Roberts (1931) concluded that convection was of minor importance and attributed layering to crystal settling.

Larsen, Hurlbut, Burgess, Griggs, and Buie (1935), after studying all the intrusive masses in the region, tentatively suggested separate consecutive intrusions as the cause of layering in the Shonkin Sag laccolith, but Hurlbut (1939) later explained the layering as the result of settling of olivine, augite, and biotite and the rise of leucite as these minerals crystallized from a homogeneous parent magma that had been intruded into the laccolith.

Pecora (1941) studied the Boxelder laccolith on the western fringe of the Bearpaw Mountains, a complex laccolith of the Shonkin Sag type, and concluded that the syenitic rocks of the Boxelder laccolith differentiated from shonkinite after emplacement of a shonkinitic magma into the laccolithic chamber.

The author (Barksdale, 1937) concentrated his study on the Shonkin Sag laccolith. He was impressed by the many obvious examples of crosscutting relationships between the various rock types, and was led to the conclusion that the primary cause of layering was separate injection of differentiates from a magmatic reservoir below. Re-consideration of his own data and a careful study of the evidence in the literature caused him to re-examine the Shonkin Sag laccolith in the field and to visit minor laccoliths in the Shonkin Sag area

and the Boxelder laccolith in the Bearpaw Mountains in 1949 and 1950 in an effort to reconcile opposing views as to the cause of the layering of the Shonkin Sag laccolith. This study led the author to revise his original hypothesis.

THE CASE FOR DIFFERENTIATION IN PLACE FROM A SINGLE INTRUSION

The author is in general agreement with Hurlbut (1939, p. 1110) that

> "the hypothesis of differentiation in place must, therefore, be supported not by clear-cut proofs but rather by the accumulation of evidence for the whole region. All the data assembled, physical, chemical, structural and petrological, are in agreement with the simple hypothesis that a homogeneous parent magma was intruded into each laccolith, where differentiation took place according to the size of the laccolith."

However, absolute proof of the origin of the layering in the Shonkin Sag laccolith by differentiation in place due to crystal settling is not to be had in the laccolith itself, for as Hurlbut (1939, p. 1110) states, "It seems impossible to set up criteria which can unequivocally prove the hypothesis of differentiation in place."

How then can probabilities be separated from possibilities? The clear-cut examples of fine-grained shonkinite cutting coarse-grained shonkinite near the margin of the laccolith; fine even-grained syenite cutting the shonkinite as a flat dike two feet thick at the westernmost margin of the laccolith; and many other cross cutting relationships were claimed by the author (1937), as evidence of separate intrusion. After a re-examination of the Shonkin Sag laccolith occurrences and those of Square Butte laccolith and the minor laccolith of Shonkin Sag, it is now apparent that the case for auto-intrusion is equally good and that injection phenomena cannot be used in a positive way by proponents of either hypothesis.

Preoccupation with the striking evidences of injection caused the author to minimize the importance of gradations between the rock types. The most completely gradational zone in the laccolith is that lying above the top of the lower shonkinite. (For general relationship of the layering, see figure 1, a.) The rock of this zone is a syenite and was called by the author (1937, p. 330) the "hybrid syenite-shonkinite." The use of the word *hybrid* was intended to imply a mixing of two magmas,

a syenitic one and a shonkinitic one .The author is now convinced that such mixing did not take place. There is a true gradation between the syenitic layer and the closely packed crystal mesh below that became the lower shonkinite. The Square Butte laccolith, the minor laccolith of Shonkin Sag, and the Boxelder laccolith each clearly show such a gradation between a syenitic layer and an underlying shonkinitic layer.

There are not enough outcrops to demonstrate conclusively over a wide area the gradation between the top of the syenite and the overlying upper shonkinite, but in the headwaters of Tanner Canyon which extends far back into the laccolith there are scattered outcrops of a blotchy, mottled zone several feet thick between these two rock types. The significance of these poor exposures was overlooked, because there is so much diverting evidence where good outcrops are available along the great cliffs at the eastern margin of the laccolith, that syenitic magma was injected into solid shonkinite (Barksdale, 1937, figs. 6, 7, pp. 336-337). The author is now convinced that auto-injection is the logical explanation for these phenomena, and that the presence of gradational zones strongly supports the hypothesis of differentiation in place.

The best evidence that differentiation in place caused the formation of the layering in all the laccoliths is summarized by Hurlbut (1939, p. 1109) as follows:

> " . . . all (the laccoliths) contain syenite and shonkinite. The syenite of the small laccoliths is of the order of 5% of the volume of the laccolith, its composition differs little from that of the shonkinite, . . .
>
> "The syenite of the intermediate laccoliths (Shonkin Sag, e.g.) is about 10% of the volume of the laccolith and is more highly differentiated from the shonkinite, than in the smaller laccoliths.
>
> "The largest laccolith (Square Butte) contains 40% of the most highly differentiated syenite . . . (which) itself shows differentiation with more mafic lower layers."

ORIGIN OF THE SYENITE LAYER

Development of the Shonkin Sag laccolith disc apparently involved fairly rapid, but probably pulsating injections of magma containing a considerable quantity of crystallized olivine, augite, biotite, and leucite which formed a nearly circular disc and broke out through its edges to form the fringing sills as the disc grew in thickness (Hurlbut 1939, p. 1104).

The chilled top and bottom of the laccolith were so imper-

vious that once injection ceased there was developed the nearest approach to a closed igneous system that one can hope to find in nature. It is probable that little differentiation took place as long as the laccolithic magma was being actively emplaced. Once the flow of magma ceased, the crystallizing olivine, augite, and biotite sank to accumulate as the mafic-enriched upper part of the lower shonkinite, each crystal as it sank displacing some of the residual liquid upward. Concurrent with the settling of the heavy minerals was the rise of early formed leucite. Hurlbut (1939, p. 1086) deduced from the increase of potash in the syenite as compared with the "transition rock" (pegmatite) that leucite had risen. The author found outlines of former leucite crystals, the mineral now recrystallized to sanidine and zeolites, to be quite marked on outcrop surfaces of the upper part of the syenite, especially in the easternmost exposures along the Shonkin Sag cliff. Outlines of former leucite crystals can also be seen in thin sections of some of the flat dikes of syenite injecting shonkinite.

The differentiated magma that accumulated between the downward freezing upper shonkinite (containing 53-49% of dark minerals by volume in its lower 20 feet) and the close-packed top of the lower shonkinite (containing 65% dark minerals) contained leucite or pseudo-leucite crystals in its upper part, a few olivine crystals and a larger number of biotite and augite crystals, both in two generations. The dark minerals were unstable and reacted with the liquid phase of the differentiate as shown by biotite rims on all of the olivine and on some of the augite, together with late biotite on early biotite. The ragged shapes of most of the augite without any traces of reaction products suggests that considerable resorption also took place, the resorbed material probably crystallizing slightly later as clean, euhedral augites of small size, too small to settle out of a solution which grew more viscous as the temperature dropped.

With continued fall of the temperature, the light differentiate crystallized to form the syenite. Plate 1 illustrates two of the textural and mineralogical characteristics of the syenite: the embayed nature of the augite and the intergrowth pattern of sanidine and sodalite, the latter mineral, however, usually replaced by a grayish aggregate of zeolites.

The dark mineral content of the upper part of the syenitic

layer averages about 25% by volume. The lower part of the syenite has about 30% dark minerals and it grades rapidly downward into the top of the lower shonkinite which contains 65% dark minerals.

The preceding reconstruction of the formation of the syenitic layer in Shonkin Sag laccolith is generally plausible for all the laccoliths in the area. Shonkin Sag laccolith, however, is unique among all the laccoliths in that it contains a very spectacular rock layer, a pegmatite, the genesis of which has not heretofore been adequately explained.

THE PEGMATITE LAYER IN THE SHONKIN SAG LACCOLITH

General Statement

The pegmatite was called by Pirsson (1901, p. 8) the "lower transition rock." Hurlbut (1939, p. 1068) following this terminology, states that:

"The transition rock separates the main syenite from the lower shonkinite." He illustrates this concept of the relations in a generalized section (1939, p. 1053.) The terminology and the diagram are unfortunately misleading. The pegmatite is not transitional between the syenite and the lower shonkinite; in reality it separates two phases of the syenite (plate 2). The lower phase is a slightly darker syenite than the main mass of syenite, but it is a true syenite texturally and mineralogically and grades downward into the top of the lower shonkinite. It is, however, sharply delimited from the pegmatite above over thousands of feet of outcrop. The relations shown in plate 2 are representative. Whereas the lower contact is an usually flat surface, the upper one has irregularities from a few inches to over a foot in vertical range.

Another anomalous relationship previously found by the author but not appreciated at the time (Barksdale, 1937, fig. 5a, p. 335) is the occurrence of sharply defined masses of syenite enclosed in the pegmatite layer. Several new occurrences of this kind were found in 1950. The syenite pieces or remnants are generally 4 to 5 inches by 14 to 18 inches in section. Some are found near the top of the pegmatite layer and some are near its base. Samples of the syenite were collected for sectioning at one locality about a foot below the top of the pegmatite layer. The rock is identical in appearance,

megascopically and microscopically, with the syenite of the main layer. These pieces of syenite crystallized under the same conditions as did the main mass of syenite, and any hypothesis as to the origin of the pegmatite cannot ignore these sharply defined masses of syenite enclosed in the pegmatite, which, must, therefore, be later than the syenite.

Texture and Mineralogy of the Pegmatite

The megascopic features of the pegmatite have been described at length by the author and by Hurlbut under the designation "transition rock." The wildly flamboyant radial clusters of acicular augite, reminiscent of some tourmaline occurrences, the intergrowths of augite and sanidine, the elongate foils of biotite, and the gigantism of minerals in general which one usually associates with pegmatites, prevented microscopic examination of the textural relations of the minerals. Recently it has been possible to make thin sections of the pegmatite and associated rocks 2½ by 3 inches in size, and these have been studied under a wide-field binocular microscope fitted with polaroid analyzer and polarizer.

No minerals other than those previously described have been discovered in this re-study, but several textural details are worthy of mention. The intergrowth between augite and sanidine or zeolitized sanidine has been called "fingerprint intergrowth" by the author and graphic intergrowth by Hurlbut (1939, p. 1069). The term graphic has not been strictly defined; but as Grout (1932, p. 247) points out, it should be reserved for those patterns that resemble cuneiform characters. Plate 3, figures 1 and 2 show the characteristic pattern of the augite of the intergrowths in the pegmatite of Shonkin Sag laccolith. It will be noted that there is little of the geometric pattern usually called graphic when speaking of the occurrence of quartz in orthoclase. The augite appears to be embayed and corroded. There are reaction rims of biotite on some of the fragments of augite and on the associated magnetite. All the augite fragments in a given area (plate 3, fig. 2) extinguish at the same time, proving that we are dealing with single skeletal crystals of large size. This alignment of apparently unconnected fragments is characteristic of the intergrowth areas, some of which have been cut parallel to and others at right angles to the c-axis of the skeletal crystals. There is only one crystal involved in some of the ovoid growths while

in others there are more than one. In the greatly elongated augite of the star clusters each ray is one ragged crystal. Some are nearly entire while others are made up of almost completely unconnected but optically oriented fragments. The space between the augite fragments occupied by zeolitized sanidine is several times wider in cross-section in some cases than the augite fragments. Only rarely has a fragment of the augite moved out of position even slightly, so that optical orientation is not quite perfect.

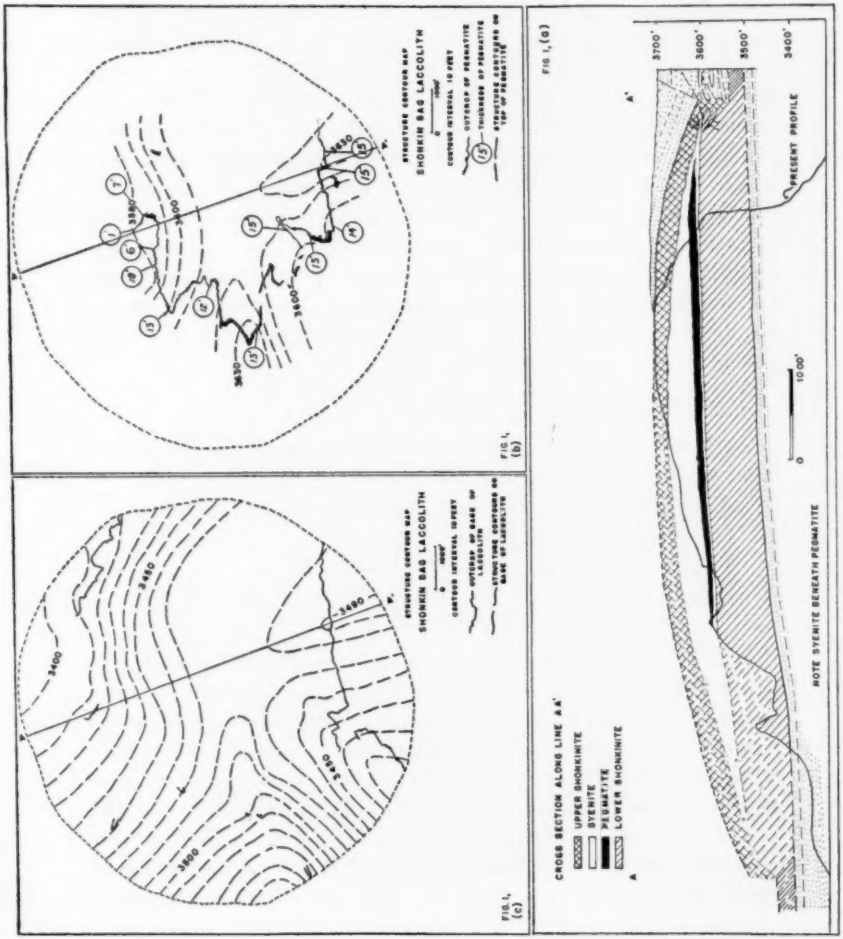


Fig. 1

Several sanidine crystals in random orientation customarily form the background for the augite fragments, but strictly speaking the skeletal augite is so large that in some areas it is technically the poikilitic host, although it is the older mineral. The growth pattern of the sanidine in the pegmatite is markedly different from that of the sanidine of the syenite. The subhedral to euhedral sanidine crystals of the syenite have a very characteristic intergrowth pattern with sodalite and other minerals now altered to zeolites. (Plate 1 illustrates the intergrowth pattern.) The sanidine in the pegmatite, generally several centimeters long, is nearly cleared of intergrowth minerals and has sharp boundaries. In many places the almost euhedral sanidine crystals have pyramidal openings between them. These spaces have been filled with late zeolites, thomsonite, and natrolite. Occasionally one finds smaller, fresh, water-clear, well terminated sanidine crystals protruding into these once miarolitic openings. There has been some attack on the sanidine by the zeolitizing solutions, but as a rule bladed natrolite enclosing titanite and aegirite fills the cavities but does not affect the sanidine. The mafics were more susceptible to the sodic solutions than was the sanidine, as shown by the fact that kelly-green rims on the augite of the pegmatite are usually found adjacent to zeolitized patches.

Origin of the Pegmatite Layer

At least three hypotheses for the origin of the pegmatite layer warrant consideration. They are:

1. Intrusion of a late differentiate from the magmatic hearth below.
2. Auto-metamorphism of the syenite.
3. Crystallization of a residual differentiate that moved into its present eccentric position by auto-intrusion.

(1) The possibility that the pegmatite represents an intrusion of a late differentiate from the magmatic hearth below cannot be dismissed. The structural control for such an intrusion can be visualized to be the plane of weakness in the syenite resulting from its final consolidation. One might expect this position of the last liquid syenite to be approximately parallel to the top and bottom of the laccolith. If an intrusion were properly timed, it is logical to expect that the pegmatite liquid would have spread out from its point of intrusion, possibly

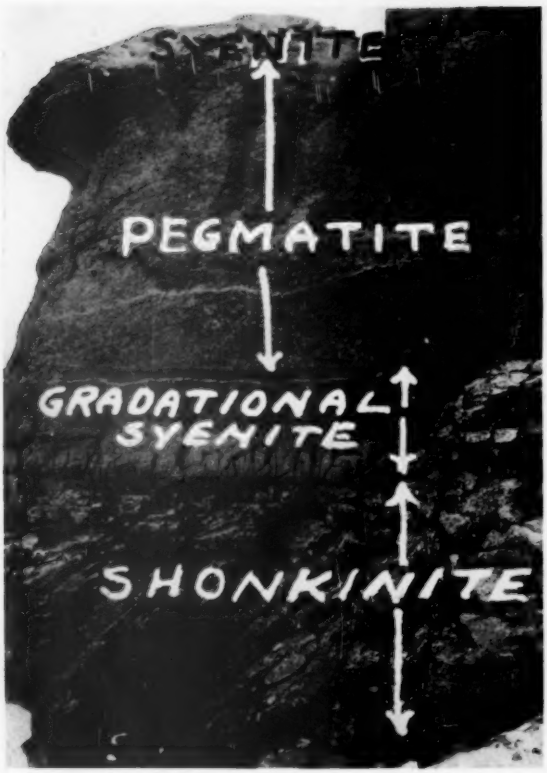
PLATE 1.

Fig. 1. Plain light.

Fig. 2. Crossed nicols.

Thin section showing two characteristic features of the syenite: first, the intergrowth of clear sanidine with gray sodalite and zeolites; second, the irregular and embayed nature of the augite. From immediately above pegmatite layer.

PLATE 2.



Cliff section of Shonkin Sag laccolith. The pegmatite layer is 13 feet thick.

PLATE 3.

Fig. 1. Fingerprint intergrowth of augite and sanidine from pegmatite layer, Shonkin Sag laccolith. Thin section, plain light.

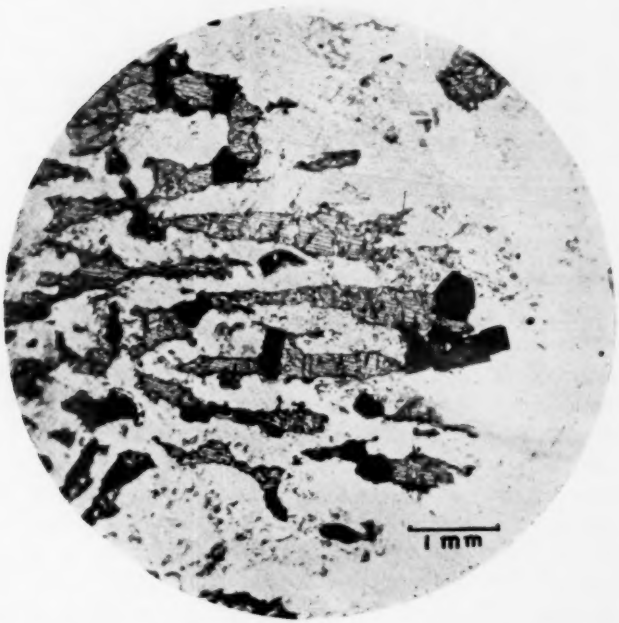
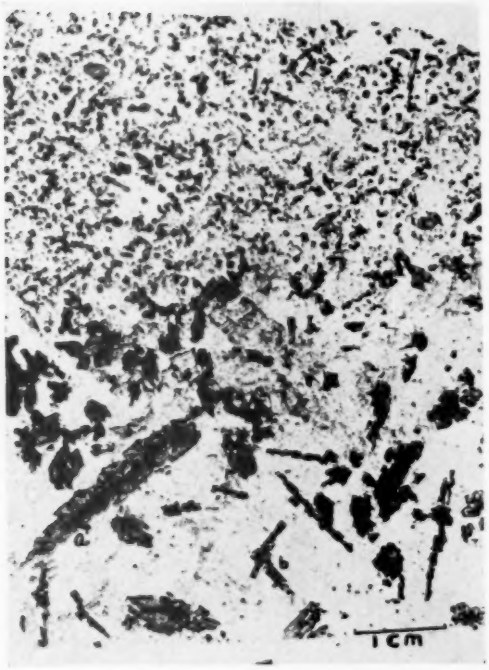


Fig. 2. Detail of intergrowth from circle in figure 1. All of the apparently unconnected pieces of augite have common extinction. Note biotite reaction rims on magnetite and, in part, on augite.

PLATE 4.



Thin section, plain light, showing contrast in texture between syenite and pegmatite, Shonkin Sag laccolith.

but not necessarily the old conduit, and, acting as a hydraulic wedge, make room for itself by lifting the solidified top of the laccolith.

The pegmatite layer is off-center both vertically and horizontally. Hurlbut (1939, p. 1085) gave a logical explanation for the vertical position of the pegmatite from a crystal differentiation standpoint. The horizontal eccentricity, however, was overlooked until the present re-study. It will be noted (fig. 1, a and b) that the greatest thickness of the pegmatite is within 1200 feet of the south edge of the laccolith, and that there is a disproportionate amount of pegmatite as compared to the thickness and distribution of the syenite layer in the laccolith. The pegmatite thins to less than one foot where last seen on the north side of the laccolith. It is true that erosion has removed all but a few feet of the overlying syenite at this point, but it is reasonable to infer that the syenite formerly had a normal thickness of about 50 feet here, as judged from the amount of shonkinite measureable below this point.

The horizontal eccentricity may be explained by local failure of the closed system in a southerly direction. The top half of the laccolith split away from the lower half along a clean line and the new magma took its present position, some of it possibly escaping to the south. That can never be proved for erosion has removed the evidence.

The hypothesis of intrusion is appealing in its simplicity. It can account for the eccentric thickness and a real distribution, for the sharp contracts, and for the relic pieces of syenite in the pegmatite as autoliths, broken off during the intrusion. In fact there is little field evidence that cannot be rather readily explained by the intrusion hypothesis.

The pegmatite is unique to the Shonkin Sag laccolith, and any explanation of its genesis must, perforce, put forward special circumstances not present in the other laccoliths. Previous objections to separate intrusion were strongly influenced by the assumption that the syenite as well as the pegmatite came in from another source. It is now agreed that the syenite layers in all the laccoliths were differentiated in place. Since the pegmatite layer is unique to the Shonkin Sag laccolith, only one separate injection is called for. This materially shortens the long arm of coincidence.

A strong objection, however, comes from reasoning rather

than from direct observation of the pegmatite-syenite relations. It is agreed that a late surge of shonkinitic magma entered the laccolith after differentiation had developed the syenite magma and caused the syenite magma to inject the already solidified shonkinite (Hurbut, 1939, p. 1086). In many places the late surge forced some of the derived syenitic magma to the extreme western edge of the laccolith where it cooled to form a flat syenite dike 2 feet thick. The late shonkinitic intrusive material from the magmatic hearth below had not appreciably changed in composition when compared with the undifferentiated frozen shonkinite of the laccolith's margins (Hurlbut, 1939, pp. 1050, 1094). It therefore becomes difficult to justify the reasoning that requires such precise timing in the magmatic hearth so that a pegmatitic magma be available at the exact time of the final consolidation of the syenite in the small, more rapidly cooling Shonkin Sag laccolith, and that it be introduced at that particular time into the Shonkin Sag laccolith only.

(2) A variation of the hypothesis that the pegmatite is the result of the final crystallization of a residual fraction involves almost complete crystallization of the syenite first and then recrystallization of a part of it to form the pematite. It has long been supposed that if during crystallization of a magmatic body the water and other mineralizers cannot escape, but are concentrated, there will be formed a very potent residual liquid capable of extraordinary powers of recrystallization. Following their recent work on the system $NaAlSi_3O_8$—$KAlSi_3O_8$—H_2O, Bowen and Tuttle (1950, pp. 510-511) point out that in deep-seated bodies the rate of heat flow from the rock mass is very small. The residual liquid will be present for an exceedingly long period. By virtue of its high water content and perhaps other potent fluxes such a residual liquid may be expected to effect complete recrystallization of early formed feldspars, with the formation of those which are in equilibrium. Bowen and Tuttle call attention to the fact that at very high pressures approaching critical end points the vapor phase formed is not greatly different in composition from the liquid phase; and this vapor phase, filling minute interstices, would also induce recrystallization even after exhaustion of all liquid.

If such processes caused the production of the pegmatite from nearly solidified syenite then the small masses of syenite

in the pegmatite represent unreplaced relics. Recrystallization from a solid explains the obvious lack of any gravitative settling of large augite and biotite crystals. The idea of replacement of older textures by recrystallization is not new, but in the Shonkin Sag pegmatite the replacing minerals are so nearly the same as those replaced that any differences obtained by ordinary optical study are not convincing. The feldspar in both syenite and pegmatite is sanidine with a very small 2V. The augite in both rocks has Z ∧ c of very nearly 45°. There is clear evidence of late sodic augite rims on older augite and late biotite on augite and on earlier biotite, but these reaction phenomena are minor and can be explained as the reactions to be expected in a magmatic stage, but prior to the stage that gave rise to the zeolitization characteristic of all the rocks of the laccolith.

The eccentric position of the pegmatite layer must be explained. Pressures within the laccolith reached a maximum during the pegmatitic stage, and the interstitially imprisoned liquid phase sought out the area of less pressure over the developing anticlines; or if the folding was not in progress at that time possibly there was a local failure of the laccolith which caused the residuum to move through the crystal meshwork to accumulate eccentrically with respect to the syenite distribution, and there exert its recrystallizing effect.

(3) Let us now consider a third hypothesis, assuming as we have that the regional evidence for gravitative crystal differentiation in all the bodies is most conclusive. What extensions or modification must we make of Hurlbut's (1939, p. 108) generalization on the origin of the pegmatite?

> "Crystallization of the rock at both top and bottom of the laccolith brought about a concentration of volatiles in the still liquid portion of the center. The layer of residual liquid is pictured as forming a few feet below the zone of any leucite concentration. The magma, enriched in volatiles, and well insulated from the cooler outer contacts, crystallized slowly and formed the coarse transition rock."

This argument is very attractive in its simplicity, but before accepting it the present author had to answer for himself several questions. What happened to the descending augite, olivine, biotite crystals of characteristic embayed habit which must have once been present in the space now occupied by the pegmatite if gravitative separation is to account for the devel-

opment of the syenite magma in the first place? What prevented the very large augites and biotites which characterize the pegmatite from settling as they slowly crystallized, through a volatile-enriched magma which traditionally has been regarded as being much less viscous than its parent? And finally, how can one account for the eccentric position of the pegmatite lens?

Thin section study shows that there has been an almost if not complete elimination of the corroded remnants of the early formed augite and olivine which occur in the syenite above and below the pegmatite and which must have once been present in the space now occupied by the pegmatite, if that pegmatite represents the solidification of a residuum. Plate 4 shows the contrasting textures. It is probable that the concentration of volatiles and the rise of pressure in this approximation of a closed system temporarily offset the effect of temperature drop and gave the solution the ability to completely resorb the mafics in approximately that part of the laccolith now occupied by the pegmatite. Then, as the temperature continued to fall, the striking fingerprint intergrowths, the star clusters of augite and the large single augites and biotite crystallized anew to form mafics whose total percentage is very close to that found in the lower syenite. In other words the mafic molecules have simply been redistributed to form large crystals and intergrowths from the material that was once in the form of many small crystals of quite different habit of growth.

The production of large crystals during a late phase of crystallization is usually ascribed to the fluxing effect of mineralizers. One suggestion from the laboratory may be of importance in support of this generalization. In recent laboratory experiments in growing halite crystals under closely controlled conditions, it was found by N. R. Mukherjee (personal communication) that when traces of lead chloride were added to the solution large, perfect crystals were grown, while in the untreated control the crystals were small and imperfect. The catalytic action of some unrecognized element or elements concentrated in the residual pegmatitic fluid may in a like manner partly account for the spectacular augite, biotite, and sanidine development.

The development of intergrowth textures (plate 3) is not well understood, but the augites of the pegmatite show every gradation from well-formed, stubby augites to ragged, embayed, elongate crystals, to the ovoid or radiating "fingerprint inter-

growth" where there is optical orientation of fragments but little or no connection between them now. The intergrowth phenomenon may offer a clue in explaining a puzzling fact about a pegmatite crystallizing from the syenitic residuum.

It is apparent when one examines the pegmatite outcrop over thousands of feet that no gravitative differentiation took place in this layer. There has been ingrained in geologic thought for a long time the assumption that a pegmatitic solution is thin, tenuous, and of high liquidity. If such was the case in the Shonkin Sag laccolith, why did not the heavy minerals of the pegmatite settle out in response to gravity as they crystallized?

One explanation is that the pegmatite layer did not crystallize slowly, but due to the fluxing effects of the high water content and/or presence of other catalytic agents in small but effective amounts, crystallization took place so rapidly that there was no opportunity for settling. The crystallization interval between augite and sanidine was so narrowed that a true intergrowth of skeletal augite and sanidine occurred.

Another possibility that must be considered is the effect of a sudden lowering of pressure by a failure in the laccolithic system. If the mafic constituents in that part of the syenite now occupied by pegmatite were held and/or put back into solution because of a pressure increase due to the concentration of volatiles, and in spite of the inevitable temperature drop, then it is to be expected that this super-saturated residuum would crystallize very rapidly if the pressure dropped suddenly. The idea of a sudden pressure drop is supported when one seeks to explain the present eccentric position of the pegmatite layer.

At some point in time between the regeneration of the pegmatite magma and its final crystallization, it moved into its present position well off center of the laccolithic disc. That it is off center can be seen when one considers the thickness of the syenite relative to the thickness of the pegmatite as shown in figure 1a. The movement of the pegmatitic magma took place subsequent to the late injection of shonkinite postulated by Hurlbut and Griggs (1939, pp. 1054, 1086, 1094) as the cause of the auto-injection of mother liquor of a partly crystallized syenite into the upper shonkonite to form sills and dikes of the aegirite syenite. There is no connection between these dikes and the pegmatite layer.

When cooling and crystallization had reduced the ratio of

residual or reconstituted magma to crystalline rock to 1 to 10 in the central part of the laccolith, the concentration of volatiles (chiefly water) would doubtless have raised the internal pressure to such a point that any weakness in the enclosing rock would be found. Structural contours show (fig. 1, b and c) that the laccolith has been warped since the development of its layering. The warping involves the top of the pegmatite as well as the base of the laccolith. It is, however, possible that the region was under folding stress at the time of differentiation and that the areas over the anticlinal noses were areas of easiest penetration by the pegmatite magma under its increased pressure. The top part of the laccolith split apart from the bottom part, as the pegmatite magma forced its way into its present position. This is true auto-injection. Folding continued after the laccolith cooled and solidified thereby involving all the layers.

If the second hypothesis is the true one then the small syenite masses enclosed in the pegmatite are unresorbed residuals rather than xenoliths torn loose from an already solidified syenite by a pegmatite magma being emplaced from the magmatic hearth below. Here, it would seem, is an opportunity to decide between the hypotheses of separate intrusion, replacement, or resorption. The small masses of syenite have texture and mineralogy identical with that of the main mass of syenite. There are no discernible differences in the contacts between the pegmatite and the small syenite masses and between the pegmatite and the main mass of syenite, and thousands of feet of outcrop of the contact between the pegmatite and the main mass of syenite have been examined. Subtle gradations from syenite to pegmatite that might reasonably be expected, if replacement were the answer, are markedly absent. The gradation is just as difficult to demonstrate at the contact between the small masses of syenite and the pegmatite. This lack weakens, for the author, the hypothesis of metasomatic autometamorphism of the syenite to pegmatite, but it does not aid in deciding between the other two hypotheses.

The question might be asked at this point as to why did not amphibole take the place of augite as the chief mafic in the pegmatite if the pegmatite formed under conditions of lowered temperature, increased pressure and high volatile content. The answer is probably twofold. First it may be pointed out that

consolidation of the syenite and pegmatite both occurred at comparatively high temperature. Sanidine is the chief feldspar in both rocks, and it is particularly clear and well formed in the pegmatite. The potash content of the magmatic residuum was so high that even at the slightly lowered temperature of pegmatite formation biotite took the place of amphibole that might be expected in normal igneous melts. It has been pointed out that biotite is one of the earliest formed minerals in the laccolith, and it occurs in every rock both as crystals and as reaction rims on all dark minerals beginning with olivine and ending with magnetite. In other words, the chemical environment was of greater importance than the slightly lowered temperature in determining the mineralogy of the pegmatite.

Amphibole did finally form in the narrow, irregular dikelet that wanders through the pegmatite layer near the center of the laccolith. The mineralogy of the dikelet has been previously discussed (Barksdale, 1937, p. 348) and nothing new can be added at this time. The sodium concentration in this stage was more important than the potash, hence the sodic amphiboles barkevikite and riebeckite and the sodic pyroxenes aegirite and acmite became more important than biotite, in the crystallized residuum of the pegmatite. It should be pointed out that even here the temperature was still high enough to cause sanidine to be the chief feldspathic mineral in the dikelet. If other feldspars or feldspathoids were formed all traces of their identity have been lost due to the pervasive zeolitization that occurred in the deuteric stage, using the word in a more restricted sense than originally proposed by Sederholm (1916).

CONCLUSIONS

It is apparent that all three hypotheses offered in explanation of the origin of the pegmatite layer have weak points or leave unexplained puzzling bits of evidence. The hypothesis of separate intrusion of the pegmatite layer has the smallest number of field or microscopic objections if the Shonkin Sag laccolith alone is considered, but there cannot be a clear cut verdict of "guilty." It is at best a Scotch verdict of "not proven."

The author, however, favors the third hypothesis. A concentration of volatiles by the downward and upward freezing of the derived syenitic magma and the attendant rise in pressure in this closed system temporarily reversed the process of

crystallization and put back into solution the earlier formed ragged remnants of augite, biotite, and leucite. A failure in the system caused the pegmatite magma so derived to migrate to its present eccentric position. The sudden release of pressure and probable loss of volatiles occasioned by the failure overcame the reversal; and augite, biotite and sanidine crystallized rapidly in the exotically large forms and intergrowths that characterize the pegmatite. Gravitative settling did not take place at this stage, probably because crystallization was too rapid.

References

Barksdale, Julian D., 1937. The Shonkin Sag laccolith: Am. Jour. Sci., 5th ser., vol. 33, pp. 321-359.

Bowen, N. L., and Tuttle, O. F., 1950. The system $NaAlSi_3O_8$ — $KAlSi_3O_8$ — H_2O: Jour. Geology, vol. 58, pp. 489-511.

Hurlbut, Cornelius S., Jr., 1939. Igneous rocks of the Highwood Mountains, Montana, Part I. The laccoliths: Geol. Soc. America Bull., vol. 50, pp. 1043-1112.

Larsen, E. S., *et al.*, 1935. The igneous rocks of the Highwood Mountains of central Montana: Nat. Research Council, Am. Geophys. Union Trans., 16th Ann. Meeting, pp. 288-292.

Osborne, F. F., and Roberts, E. J., 1931. Differentiation in the Shonkin Sag laccolith, Montana: Am. Jour. Sci., 5th ser., vol. 22, pp. 331-353.

Pecora, W. T., 1941. Structure and petrology of the Boxelder laccolith, Bearpaw Mountains: Geol. Soc. America Bull., vol. 52, pp. 817-854.

Pirsson, L. V., 1905. Petrography and geology of the igneous rocks of the Highwood Mountains, Montana: U. S. Geol. Survey Bull. 237.

Sederholm, J. J., 1916. Synantectic minerals and related phenomena: Comm. géol. Finlande Bull., vol. 48.

Weed, W. H., and Pirsson, L. V., 1895. Highwood Mountains of Montana: Geol. Soc. America Bull., vol. 6, pp. 389-422.

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PLEISTOCENE CLASTIC DIKES IN WEATHERED GRANITE-GNEISS, RHODE ISLAND

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ABSTRACT. Clastic dikes occur in weathered granite-gneiss in North Scituate, Rhode Island. They fill joint fissures in the bedrock and are vertical, inclined, or essentially horizontal. The dikes range in length from a few inches to more than 20 feet, and their thickness is usually less than 6 inches. Upon the bedrock is a discontinuous layer of till overlain by material of eolian origin. The clastic dikes have been derived from the Pleistocene mantle of till and loess overlying the bedrock. It is believed that the dike material slumped downward along joint fissures held open by ice veins shortly after retreat of the last ice sheet from the area.

INTRODUCTION

THE clastic dikes described in this paper are about 9 miles west of the center of Providence, Rhode Island, along U. S. Highway 6 (fig. 1). The dikes are located on the south slope of a hill about one-half mile southeast of the village of North Scituate. They are exposed in a group of pits from which the town of North Scituate is removing "rottenstone" for road metal.

GEOLOGIC SETTING

The bedrock is Sterling granite-gneiss, a moderately coarse-grained rock, non-uniformly weathered, and locally termed "rottenstone." It is overlain by a discontinuous layer of light-colored, sandy glacial till which reaches a maximum thickness of 3 feet. Where till is absent, eolian material rests directly upon bedrock. A thin surface soil 3 or 4 inches thick has been developed, but no other soil horizons were found. The clastic dikes occupy joints in the bedrock. These relations are shown in the composite section (fig. 2). The figure is diagrammatic in that not all the samples were collected from the same locality.

The Sterling granite-gneiss, which shows little foliation at this locality, is intruded by bands of aplite and of pegmatite. Joints are numerous and closely spaced, many being little more than a foot or two apart. They form a network of rudely developed sets which are vertical, inclined, and essentially horizontal. A few small open joints were found both in weathered and in firm rock, but most of the joints are tight or are filled with clastic material.

The maximum depth of weathering in the bedrock could not be determined. Some of the deepest of the vertical sections, which were cut to about 8 feet below the bedrock surface, failed to expose firm rock. The aplite has remained relatively firm, but many of the coarse-grained, well-jointed portions of the rock are so thoroughly weathered that the rock can be crumbled by hand. On other exposures, weathering has affected only a surface skin a fraction of an inch thick.

Weathering has not seriously decomposed individual mineral grains. Examination by petrographic microscope shows no great alteration of feldspars or of the easily decomposed biotite, amphibole, or magnetite. It would seem that weathering served principally to loosen the grains by slight alteration along grain boundaries or cleavage planes.

The till is light gray, sandy, and forms a discontinuous cover on bedrock. It shows no weathering other than development of the present surface soil, a layer 3 or 4 inches thick composed of weathered till and humus. The till contains boulders and pebbles of Sterling granite-gneiss and rocks of other types, some of which, including the Sterling granite-gneiss, are thoroughly weathered. In several exposures, fresh and weathered boulders are in close proximity. In a pit near the top of the hill, glacial striations occur on the surface of the exposed bedrock. These indicate ice motion in the direction of S. 15° E. (fig. 1).

At one locality the base of the till is laminated (plate 1). The origin of this lamination is not clear. The laminated layer is 1 inch thick and rests directly upon bedrock. It can be traced for a distance of 5 feet, and it passes without appreciable change in thickness over irregularities of the bedrock surface. The base of the layer consists of a thin film of clay. Above the clay, and distinct from it, is material of silt size, and this grades upward into fine sand.

Overlying the till, and resting directly upon bedrock where till is absent, is material of eolian origin, which was probably deposited shortly after retreat of the last ice sheet. The material does not completely resemble the loess of midwestern United States, but for convenience it is called loess in this paper. The deposit ranges in thickness from 6 inches to about 3 feet. Most of the material is yellow or brownish-yellow in color, but a surface zone 3 or 4 inches thick has been oxidized

to a dark brown color. The deposit is discontinuous, probably because there has been some removal by erosion. About 90 per cent of the material is composed of angular to subangular quartz grains of silt and fine sand sizes. The loess contains pebbles and cobbles, some of which are weathered Sterling granite-gneiss. The pebbles and cobbles were probably introduced by frost heaving from below or by slope-wash. No bedding or other structures were found in the loess. Similar material has been described from the vicinity of Boston by Smith and Frazer (1935, pp. 16-32) and from southern Connecticut by Denny (1936, pp. 333-335).

DESCRIPTION OF THE CLASTIC DIKES

The clastic dikes form an intricate network in the granite-gneiss. The longest dikes exposed extend more than 20 feet along the trace and are essentially horizontal. Dikes range in

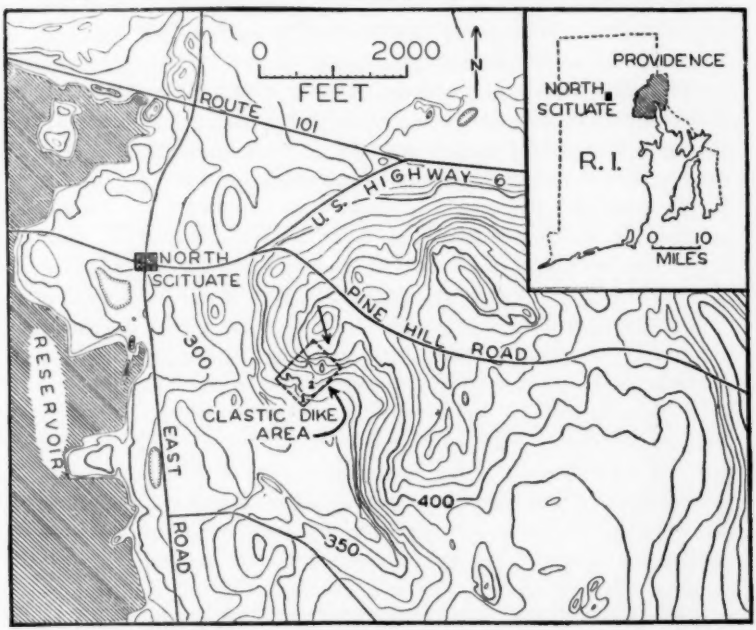

Fig. 1. Location and topography of the clastic dike area. Small numbers 1 and 2 within the dashed rectangle refer to described localities. Arrow north of the dashed rectangle indicates direction of ice motion, as shown by striations on bedrock.

thickness from a fraction of an inch to a maximum of 6 inches, but the thickness of any individual dike is relatively uniform. Vertical dikes seem to be thicker in general than those more nearly horizontal, but no other consistent relation between position and thickness was observed. As many of the longer dikes extend to the base of each exposure, the maximum depth to which the clastic dikes extend could not be determined.

Extent of weathering in the bedrock has had no effect on distribution of the clastic dikes, for they extend unbroken through firm and disintegrated rock alike. In general the joint surfaces are smooth, and the contact between dike material and wallrock is sharp. In many places bits of weathered bedrock occur in the dikes. In some cases no indentation could be found in the wallrock corresponding to an adjacent fragment in the dike matrix, indicating that the wallrock fragment had been displaced from its point of origin.

Apparently the dike material has been derived from whatever type of surface material directly overlies the bedrock. There is no striking change in appearance between till and underlying clastic dikes. Many of the wider, nearly vertical dikes extending downward from the till-bedrock contact contain foreign pebbles and matrix clearly derived from the till. The dike material is finer in grain downward, indicating that the larger particles did not find their way downward as readily as did the smaller ones. The dikes immediately below loess appear to be composed of loess and contain few foreign pebbles. This field evidence has been confirmed by sedimentary analysis.

The dikes are well exposed at locality 1 in the southern corner of the group of pits (figs. 1 and 2), where the exposure extends 10 feet below the surface. Here till overlies the bedrock at most places, but it is thin and pinches out laterally. The upper blocks have been somewhat disturbed and rotated upward into the overlying material, as near D in figure 2. Below these blocks the till material grades downward into true clastic dikes. At this locality are exposed long, thin, nearly horizontal clastic dikes spaced about 1 foot apart (fig. 2). Four of these dikes are particularly well defined and can be traced about 20 feet. They are straight and are uniform in thickness. Transecting these horizontal dikes are numerous vertical and inclined dikes, producing a pattern of separate bedrock blocks. One of the smaller blocks about one foot in diameter was removed intact by the writer. It appeared to

have been completely enclosed by dike material at the sides, top and bottom. Some of the shorter dikes in this exposure gradually pinched out and disappear laterally. Others are arcuate in vertical section, filling a set of short joints with changing dip. One dike, composed of fine sand, occurs 6 feet below the bedrock surface. It is 6 inches thick and nearly horizontal.

Figure 3, also at locality 1, represents a vertical section whose upper margin is 3 feet below the bedrock surface. An area about 3 feet long and 1 foot wide is enclosed by several relatively large blocks of granite gneiss and contains many small, irregular fragments. The boundaries of the fragments are indistinct and the rock grades out into the clastic material.

The exposure represented by plate 1 was found at locality 2, about 100 feet northeast of locality 1. The bedrock is highly disintegrated, but has a relatively smooth surface. The previously described, thin laminated band at the base of the till occurs in this section. This band can be seen in the photograph (plate 1, fig. 1). Wherever the base of the till crosses a clastic dike in the underlying bedrock, the lamination is indistinct or disappears. This may indicate that the till was laminated befor the emplacement of the dikes, although later settling of the dike material might obscure earlier lamination. A clastic dike

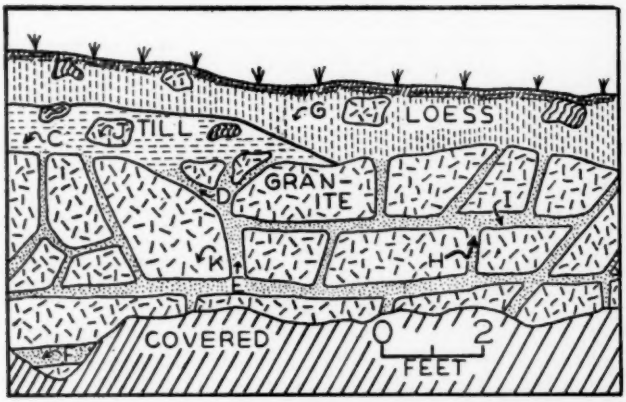

Fig. 2. Composite diagrammatic sketch of a vertical section illustrating field relations of loess, till, bedrock, and clastic dikes. Letters refer to samples collected. Thicknesses of many of the dikes are considerably exaggerated.

extending horizontally from the base of the till into the bedrock shows similar lamination (plate 1, fig. 2). Another dike, 10 inches below the bedrock surface and dipping 15 degrees, is also laminated. Although lamination was rarely found in other places in the clastic dikes, wherever it could be recognized it was found to be of the same type. The dikes which exhibit this lamination are horizontal or nearly so. Their maximum dip does not exceed 15 degrees.

RESULTS OF SEDIMENTARY ANALYSIS

Sedimentary analyses were performed on eleven samples of till, loess, dike material, and weathered bedrock collected in the area. Results are presented in figure 4 and in table 1. The samples were quartered to portions weighing approximately 45 grams. Of each portion the material finer-grained than .0625 mm was dispersed by sodium oxalate and elutriated by the pipette method (Krumbein and Pettijohn, 1938, pp. 166-172). Coarser-grained material was sieved.

Results of the sedimentary analysis show that the clastic dikes are composed of material very similar to that of the Pleistocene mantle overlying the bedrock. Where the mantle is till, the dikes are composed of material seemingly derived from till; where the mantle is loess, the dikes are composed of material seemingly derived from loess.

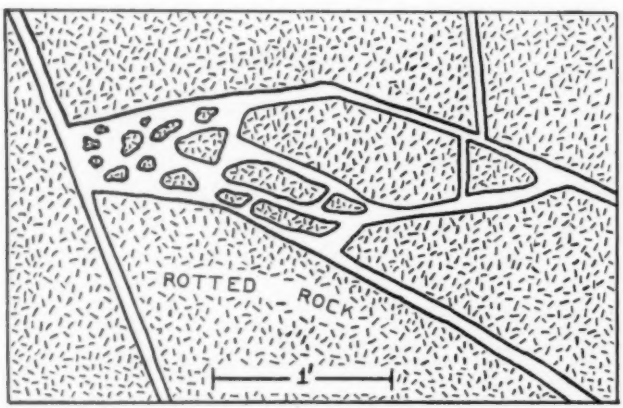

Fig. 3. Sketch of section exposed at locality 1, showing fragments of weathered bedrock imbedded in matrix of clastic dike material.

TABLE 1

Statistical results of sedimentary analysis. Q_1 and Q_3 are first and third quartiles, respectively. Md is the median diameter. QDa and Ska are arithmetic quartile deviation and arithmetic skewness, respectively. So is the Trask sorting coefficient, and Sk is the Trask skewness, which is the square of geometric skewness.

SAMPLE	TYPE OF MATERIAL	Q_1*	Md*	Q_3*	QDa	Ska	Sk	So
A	Till	00.52	0.15	0.08	0.22	0.15	1.80	2.60
B	Till	01.50	0.23	0.08	0.71	0.56	2.10	4.50
C	Till	10.00	0.34	0.12	4.90	4.72	10.80	8.90
D	Dike below till	01.75	0.40	0.15	0.80	0.55	1.64	3.42
E	Dike below till	01.40	0.37	0.13	0.63	0.39	1.35	3.26
F	Sand dike 6 feet below base of till	00.27	0.16	0.09	0.09	0.02	1.00	1.67
G	Loess	00.36	0.09	0.05	0.16	0.12	2.28	2.76
H	Dike below loess (vert.)	00.21	0.09	0.04	0.08	0.04	0.99	2.45
I	Dike below loess (horiz.)	00.23	0.07	0.03	0.09	0.06	1.59	2.60
J	Weathered bedrock boulder in till	....	1.40	0.40	...	...	...	...
K	Weathered bedrock	....	...	0.74	...	...	...	...

*Diameter in millimeters.

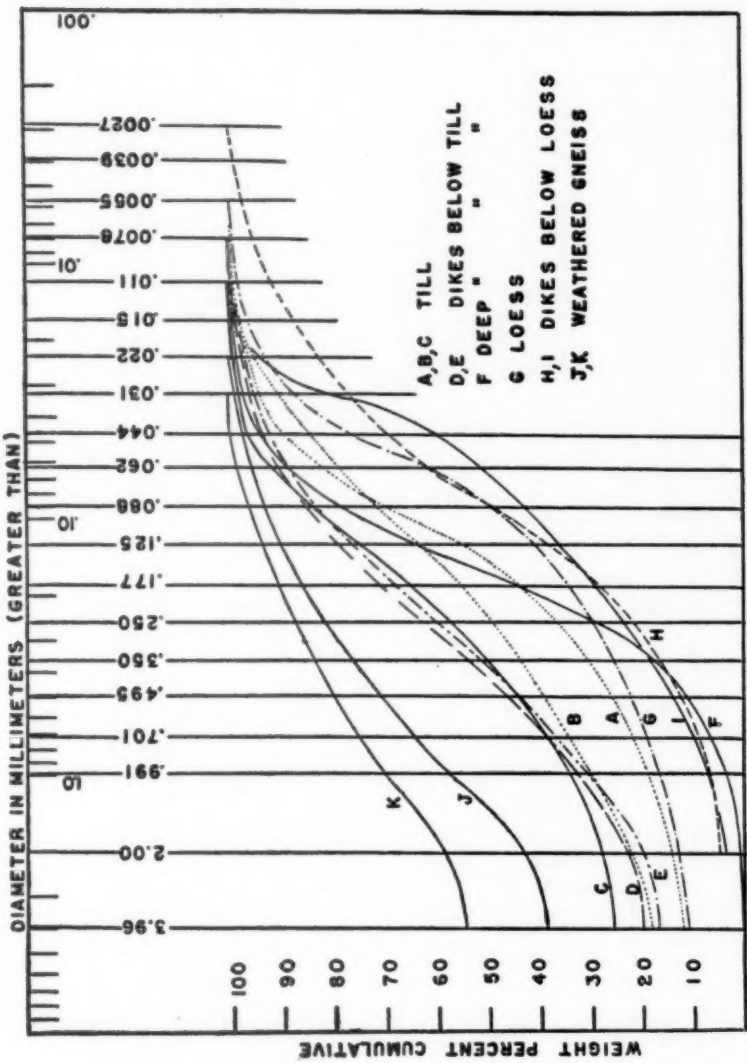

Fig. 4. Graphical presentation of results of sedimentary analyses. Weight per cent is plotted against grain diameter in millimeters. Vertical lines intersected by the curves indicate the size of openings in the sieves used. Till samples A and B were collected at some distance from the other samples.

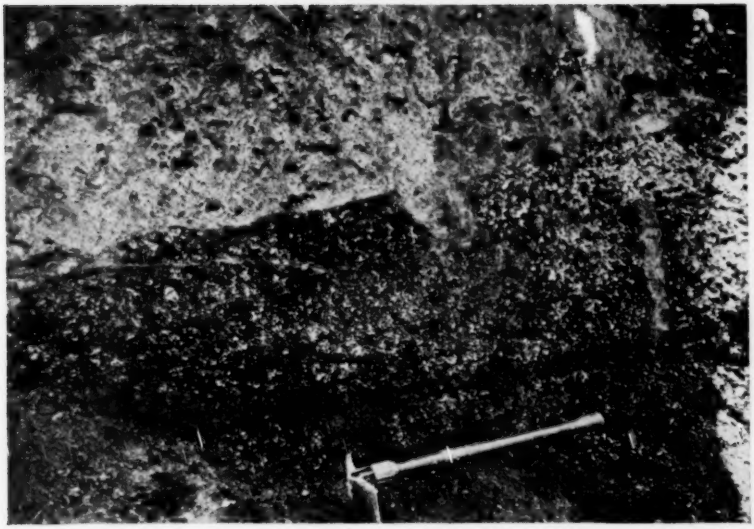

Fig. 1. East wall of pit at locality 2, showing till, bedrock, and clastic dikes. The bedrock is extensively disintegrated. Light band just above the dark bedrock area is laminated layer at base of the till. For diagram see figure 2 below.

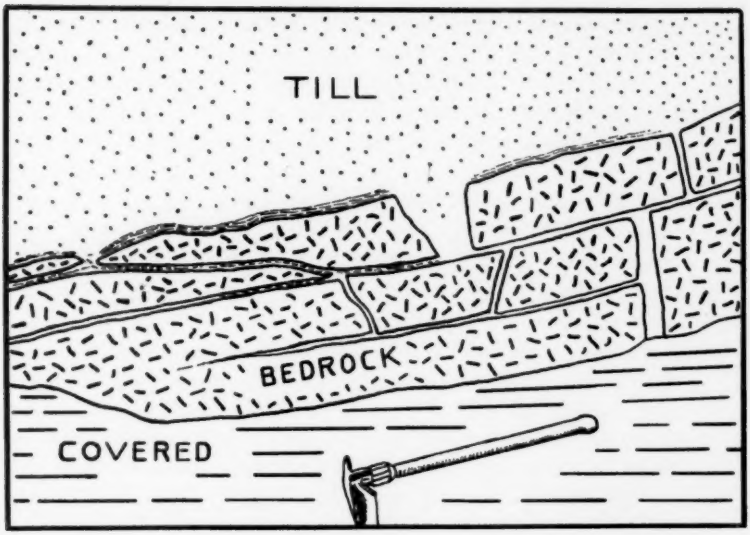

Fig. 2. Locality 2. Diagram made from photograph, figure 1 above. Fine broken lines at base of till and in some of the dikes represent lamination. Length of shovel handle is 20 inches.

Field relationships of the various samples are illustrated in figure 2. The figure is diagrammatic, because not all the samples were collected from the same locality. Till samples A and B were collected at the top of the hill, several hundred yards distant from the other samples, where a cellar excavation provided excellent exposures of the till. These samples were studied merely for comparison with the till overlying the clastic dikes. H and I were collected at locality 2, and the remaining samples are from locality 1.

Cumulative curves (fig. 4) are in several groups. There is close coincidence of the curves for till sample C and the clastic dike samples D and E. Till lies directly upon the bedrock surface above the dikes from which D and E were collected. Curves for till samples A and B also fall close together. The curve for the well-sorted dike sample F seems to fall closer to the curves for till samples than the curve for loess or dikes below loess. It is composed of finer material than the till samples and is the deepest of the dike samples collected. However, it is coarser than the loess or the dike material below loess, which would seem to exclude the possibility of its having been derived solely from that material. It may be composed of material derived from both till and loess, its greater depth providing opportunity for mixing during the emplacement process. The curves for loess sample G and for the dike samples H and I, which were collected where loess directly overlies bedrock, are also clearly grouped. As would be expected, this material is finer grained than the till or the dike material below till.

Statistical values presented in table 1 fall into similar groups. Median diameter (Md) and quartile deviation (QDa) show correspondence for each type of material. Skewness values (Sk) are generally greater than 1, which means that the mode, or size of greatest frequency, lies on the fine side of the median. Trask's (1932, pp. 70-72) sorting coefficient (So), which decreases in magnitude as excellence of sorting increases, shows poorer sorting in the till and dikes below till than in the loess and underlying dikes. Till sample A, however, shows sorting comparable to that of the loess and the loess dikes. This is due to the presence of wallrock fragments in the loess dikes and the pebbles in the loess introduced after its deposition. These fragments and pebbles could not be com-

pletely eliminated, and it was thought best to analyze the sample as it was taken from the field. Had this foreign material been eliminated, the loess and the loess dikes would show even better sorting coefficients. Moreover, since the median diameter of grain size for the loess dikes would be smaller, the three curves would shift farther to the right, away from the other curves in figure 4.

The grouping of curves and of statistical values for each type of material strengthen field evidence that the clastic dikes have been derived from whatever material directly overlies the bedrock in which they occur.

MODE OF ORIGIN OF THE CLASTIC DIKES

As the clastic dikes were derived from overlying till and loess, their emplacement could not have begun prior to the deposition of the till. As some of the dikes are derived from loess, which is younger than the till, the process of emplacement must have taken place at least in part after retreat of the ice. In the few cases where open or partially filled joints were observed, it appears that clastic material which filled these joints has been washed out comparatively recently. There is no evidence that these joints are being refilled, and there is no indication of modern subsurface disturbance. Thus it is reasonable to conclude that the process of emplacement of the clastic dikes is not going on at present.

Goldthwait and Kruger (1938, p. 1192) and Kruger (1938, pp. 305-307) describe similar clastic dikes in New Hampshire. The dikes form a network along joints in weathered bedrock which is overlain by till. They are less than 1 inch thick and can be traced 10-20 feet. Some are composed of finely laminated silt. As interpreted by the authors (Goldthwait and Kruger, 1938, p. 1197), some of the finer-grained till material was injected into the fissures by the pressure of the overlying ice. This hypothesis cannot be applied to the dikes at North Scituate, as formation of those dikes derived from loess must have occurred after disappearance of the ice.

Emplacement from below as described by Diller (1889) and by Walton and O'Sullivan (1950) is obviously inapplicable to the clastic dikes in Rhode Island, for they are in granite-gneiss.

An alternate seismic theory of origin, based upon shaking and disarrangement of the bedrock blocks during earthquakes

and settling of overlying material into the joints, is discarded for the following reasons: (1) especially in the case of the horizontal dikes, it would be extremely difficult to explain the uniform thickness of each dike by a process involving disorder; (2) the bedrock blocks appear to be little rotated or disarranged; the pattern which they form seems to have been dilated, not distorted, by the presence of the clastic dikes (fig. 2, and plate 1, fig. 2).

The hypothesis is here advanced that the joints were opened by ice veins, that these veins melted irregularly, and that during the time of melting, clastic material moved into joints still held open by remnant patches of ice. During early stages of the process, the bedrock blocks would be supported mostly by ice. The clastic material, having perhaps been frozen and containing masses of ground ice would in thawing become saturated and so mobile that it could flow into the fissures as a plastic paste. Thus as the ice veins melted, the role of supporting the bedrock blocks would gradually pass from the ice vein remnants to the clastic dikes. Deposition in this manner might also account for the lamination in some of the flat-lying dikes. There seems to be no apparent reason for persistence of the fine material at the base. Perhaps this persistence is not universal, and lamination in the reverse order was overlooked or was not exposed.

Without involving formation of ice veins, it might be argued that mass movement alone resulted in opening even the horizontal fissures. With slight relative displacement effected by downhill creep of the bedrock blocks, the fissures could have been held open by opposed irregularities on the joint surfaces. If such opposed irregularities or projections formed the supports between blocks, the chances of transecting some of these irregularities would be good, as the available exposures and the directions of vertical sections are numerous, and the area of each exposed section is much larger than the area of the averaged block surface in the section. Such irregularities were not revealed in the vertical sections of the quarry or on any surface of the block which the writer was able to remove intact. The evidence strongly suggests that bedrock blocks are at present supported almost if not entirely by the clastic material upon which they rest.

Ice veins and layers in surficial materials in Alaska have

been studied by Taber (1943, pp. 1510-1529). Such features occur only in regions of perennially frozen ground. Wernecke (1932, pp. 41-43) describes ice veins in solid rock at Keno Hill, Yukon Territory. Here the mean annual temperature at the surface is 2° or 3° C. below freezing. Most of the veins are from 25 to 30 feet long and not over 6 inches wide. They are more numerous within 100 feet of the surface, but some are at depths of more than 300 feet. They are both in quartzite and in friable slate. Wernecke (1932, p. 41) believes that the ice veins widened the fractures in which they are found, because the slate is too friable to contain open fractures. In one shaft an ice vein 3 inches thick was found along a fault dipping 25 degrees. Above the ice on the hanging wall of the fault was a layer of frozen gouge, also about 3 inches thick. The gouge became a soft black mud and collapsed when thawed. This shows that an open fissure could not have existed before freezing occurred and the ice veins developed.

ENVIRONMENTAL IMPLICATIONS

The formation of ice veins implies perennially frozen ground, which in turn implies a climate much colder than that of the present. Perennially frozen ground forms only where mean annual temperature is below 0° C. (Taber, 1943, p. 1506; Muller, 1947, p. 4). The mean annual temperature in Rhode Island for the years 1904 to 1947 inclusive is 10° C. Thus the temperature change since the formation of the clastic dikes must have been 10° C., or more.

A former existence of a colder climate is corroborated by Denny (1936, p. 342), who writes that periglacial features are common in the northeastern United States. He describes involutions and soil tongue phenomena in southern Connecticut, and he believes that these are ground ice phenomena developed under conditions of periglacial climate. Sharp (1942, pp. 115-126) describes involutions in Illinois, and Schafer (1949, pp. 156-171) describes similar features in central Montana. Schafer (written communication, 1949) has also observed involutions at several localities in Rhode Island.

The lack of a soil profile on the surface of the till where it underlies loess strongly suggests that the loess was deposited so soon after withdrawal of the glacier that there was not enough time for soil to be developed. Smith and Frazer (1935, pp. 30-31) point out that loess tends to preserve past weather-

ing effects developed in underlying material. Inasmuch as the underlying till at North Scituate is fresh, both materials seem to have been deposited as a result of the same glaciation.

Flint (1947, p. 460) points out that evidences of former frozen ground in northeastern Europe are found within 150 miles of the maximum southerly extent of the former Scandinavian Ice Sheet. It is likely that in southern New England the width of the belt containing frozen ground features was not so great as that in Europe, because southern New England is approximately 10 degrees more southerly in latitude than is the area in Europe reached by the Scandinavian Ice Sheet at its maximum extent. It can thus be presumed that the ice veins preceding the clastic dikes were formed while the ice margin was well within 150 miles of North Scituate, Rhode Island.

A climatic environment favorable for formation of ice veins might have existed not only in zone marginal to retreating ice, but also in front of advancing ice. Thus it might be argued that after retreat of the ice that deposited the till in North Scituate, the ice readvanced close enough to the area to subject it once more to conditions of perennially frozen ground. Till younger than that at North Scituate would then be deposited throughout the area covered by ice during readvance. However, no later till mantle has as yet been reported in southern New England north of the clastic dike area. It is therefore concluded that the ice veins were formed during retreat of the last ice sheet in southern New England and while its margin was still within 150 miles of North Scituate. The age of the clastic dikes, formed as the ice veins melted, is probably late Pleistocene.

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REFERENCES

Denny, C. S., 1936. Periglacial phenomena in southern Connecticut: Am. Jour. Sci., 5th ser., vol. 32, pp. 322-342.

Diller, J. S., 1889. Sandstone dikes: Geol. Soc. America Bull., vol. 1, pp. 411-442.

Flint, R. F., 1947. Glacial geology and the Pleistocene epoch, John Wiley & Sons, Inc., New York.

Goldthwait, J. W., and Kruger, F. C., 1938. Weathered rock in and under the drift in New Hampshire: Geol. Soc. America Bull., vol. 49, pp. 1183-1198.

Kruger, F. C., 1938. A clastic dike of glacial origin: Am. Jour. Sci., 5th ser., vol. 35, pp. 305-307.

Krumbein, W. C., and Pettijohn, F. J., 1938. Manual of sedimentary petrography, D. Appleton Century Co., New York.

Muller, S. W., 1947. Permafrost or permanently frozen ground and related engineering problems, J. W. Edwards, Ann Arbor, Michigan.

Schafer, J. P., 1949. Some periglacial features in central Montana: Jour. Geology, vol. 57, pp. 154-174.

Sharp, R. P., 1942. Periglacial involutions in northeastern Illinois: Jour. Geology, vol. 57, pp. 113-133.

Smith, H. T. U., and Frazer, H. J., 1935. Loess in the vicinity of Boston, Massachusetts: Am. Jour. Sci., 5th ser., vol. 30, pp. 16-32.

Taber, S., 1943. Perennially frozen ground in Alaska: its origin and history: Geol. Soc. America Bull., vol. 54, pp. 1433-1548.

Trask, P. D., 1932. Origin and environment of source sediments of petroleum, Gulf Publishing Company, Houston, Texas, pp. 67-76, 94-95.

Walton, M. S., and O'Sullivan, R. B., 1950. The intrusive mechanics of a clastic dike: Am. Jour. Sci., vol. 245, pp. 1-21.

Wernecke, L., 1932. Glaciation depth frost, and ice veins of Keno Hill and vicinity, Yukon Territory: Engin. Min. Jour., vol. 133, pp. 38-43.

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THE EFFECT OF URANIUM-VANADIUM DEPOSITS ON THE VEGETATION OF THE COLORADO PLATEAU*

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ABSTRACT. A study has recently been made by the U. S. Geological Survey of the relation of plants to uranium-vanadium deposits in several districts of the Colorado Plateau. The deposits occur mainly in the Salt Wash sandstone member of the Jurassic Morrison formation. The ore contains unusual concentrations of uranium, vanadium, and selenium, and plants growing near shallow ore deposits accumulate small amounts of these metals. To investigate the extent of this relationship, basic biogeochemical studies were made in the Thompsons district, Grand County, Utah. The information gained from these studies is being used in the development of biogeochemical methods of prospecting for uranium ores in sandstones of the Colorado Plateau.

Three lines of investigation have been pursued. The effects of these concentrations of metals on plant growth have been observed, the absorption of uranium and vanadium by plants has been investigated, and the ecology of the plants in several uranium districts has been studied. Because of the association of selenium-indicator plants with the uranium deposits of the Thompsons district, the distribution of various species of indicator plants was mapped in detail.

Four conclusions have been drawn from this work. First, the plants growing on dumps and areas of mine seepage where the metals are oxidized show chlorotic symptoms and dwarfing, but those rooted in unoxidized ore are not noticeably affected. Second, it has been demonstrated that plants absorb small amounts of uranium and vanadium that can be detected by analyzing a given part of the plant. The amount of uranium is consistently greater where the plants are rooted in ore than where rooted in barren sandstone. Third, a uranium-tolerant flora has been recognized and a list of the plants compiled from a study of thirteen areas. The flora is characterized by selenium-indicator plants and by sulfur-accumulating members of the mustard and lily families. Fourth, where selenium-bearing ores lie at shallow depth and where the geography and rainfall are favorable for plant growth, the distribution of selenium-indicator plants is shown to accord with that of the carnotite ores. Certain species of selenium-indicator plants, depending on the quantity of selenium in the ore, can be mapped in a particular area as a guide to exploration.

INTRODUCTION

THE U. S. Geological Survey is conducting at the present time a long-range program of exploration and geologic studies of uranium deposits in the Colorado Plateau under the auspices of the Atomic Energy Commission. A special research project has been in progress since the spring of 1949, as a part of this program, to determine whether biogeochemical prospect-

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ing could be used as a tool in the search for this type of ore. In particular, prospecting by plant analysis as used in Sweden (personal communication from Josef Eckland, Swedish Geological Survey) for locating a vanadium-bearing shale and the use of selenium-indicator plants as suggested by Beath (1943) have been investigated.

In the course of this study, many data have been acquired on the effects of uranium-vanadium ore bodies on plant growth. The tolerance of various species for large amounts of uranium, vanadium, and selenium in the soil has been studied, and several thousand samples of plant material were analyzed to determine the absorption of these elements by plants. These data, of interest to botanists as well as to geologists, are presented in this paper. The application of these relationships in prospecting for uranium will be discussed in a later paper.

Samples were collected, and geology and plant distribution were mapped by the author and four assistants—John R. Harbaugh, Mary E. Durrell, Richard Stillman, and Louis C. Rove, Jr. The chemical analyses of the plants and rocks on which conclusions were based were made by members of the Trace Elements Laboratories in the Geochemistry and Petrology Branch of the U. S. Geological Survey. Ruth Kreher, Fred Ward, and Claude Huffman are responsible particularly for developing chemical techniques and for ashing and analyzing many of the samples.

GEOLOGY AND GEOGRAPHY

The uranium deposits of the Colorado Plateau are of wide areal distribution and occur in sandstones of similar lithology in several formations of Triassic and Jurassic age. The deposits under immediate biogeochemical study are restricted to the Jurassic Morrison formation, which comprises two lithologic units of about equal thickness; the lower unit, the Salt Wash sandstone member, and the upper unit, the Brushy Basin shale member.

Most of the uranium deposits are in the sandstone beds near the top of the Salt Wash sandstone member or in the basal conglomerate of the Brushy Basin shale member of the Morrison formation. The ore bodies are extremely spotty in distribution and form irregular, elongate, tabular masses that lie in lenses essentially parallel to the sandstone beds. The lenses range from

1 to 60 feet in thickness and from a few feet to several thousand feet in length. Those of the Thompsons district, where most of the botanical studies were made, are comparatively small. Uranium- and vanadium-bearing sandstone that averages about 0.25 per cent U_3O_8 and 2 per cent V_2O_5 constitutes ore. Carnotite, which is yellow, is the principal uranium mineral. Minor amounts of selenium, molybdenum, lead, cobalt, nickel, chromium, and copper are associated with the ore. Mudstone is normally interbedded with the sandstone. This mudstone is red except where it underlies a bed containing ore, and there it is blue green. More detailed descriptions of the uranium-vanadium deposits are contained in reports by Fischer (1942; 1950), from which this brief description has largely been taken.

The Thompsons district is 15 miles southeast of Thompsons, Grand County, Utah. The altitude of this area is about 4,900 feet. The climate is semiarid, and the annual rainfall is less than 7 inches. The erosion of the mudstone interbedded with the sandstone has produced a typical badland topography. The vegetation is of the desert type, with blackbrush and saltbush predominating; taller shrubs, scrub oak, and juniper grow on certain of the higher mesas. Ecologically the alkaline environment is ideal for the development of selenium-indicator plants of the *Astragalus* group that abound in the district. The distribution of these plants is controlled by selenium, which is associated with the uranium ore bodies. The Carrizo district, in northeastern Arizona, where corroborative plant data were acquired, has a similar ecology and geographic setting.

Studies were made of the plants on some of the higher mesas of southwestern Colorado, where the environment is somewhat different. These mesas range from 6,000 to 8,000 feet in altitude and receive an annual rainfall of about 15 inches. The vegetation is predominantly juniper and pinyon with an undergrowth of rosaceous shrubs and tender herbaceous annuals. Sagebrush and saltbush grow in the drier areas. Selenium-indicator plants of the *Astragalus* group are scarce at altitudes above 6,000 feet. *Stanleya pinnata*, however, is unaffected by altitude.

RELATION OF PLANTS TO ORE DEPOSITS

The chemical environment of an ore deposit affects the plants growing near the deposit in three ways. First, the metabolism

of the plants may possibly be affected by the unusual amounts of ore minerals available to the roots, so that the plants exhibit anomalous growth habits. Second, some species of plants absorb and accumulate available elements in detectable quantities. Third, the chemical environment can restrict the distribution of certain plants and thus create an indicator flora. Under proper environmental conditions, these three effects on plants can be used in prospecting for ore bodies.

Anomalous Growth Habits

The effect of uranium on plant growth was first studied in Japan by Loew (1902) and Asō (1903), who found small amounts of uranium to be stimulating to plant development. More recently, plant physiologists Stoklasa and Penkava (1928, 1932), Hoffmann (1942), and Drobkov (1937, 1940, 1951) have shown that uranium, radium, and thorium are necessary nutrient substances for higher plants. The amount needed is infinitesimal, and concentrations above a very low level are retarding or even toxic.

Early work with one-celled microorganisms by Bequerel (1913), Agulhon and Sarzarac (1913), and Agulhon and Robert (1914) demonstrated that bacteria grown in a culture containing an optimum amount of uranium are stimulated in growth but are retarded at higher concentrations. Agulhon and Robert found 12 to 24 ppm of colloidal uranium to be most favorable for the development of pyocyanic *Bacillus*. Stoklasa and Penkava (1928, 1932) found *Azotobacter*, the nitrogen-fixing bacteria, to be stimulated in cultures containing up to 4.7 ppm uranium and to be inhibited at higher concentrations. Kayser (1921) has also shown that uranium nitrate increases nitrogen-fixation by *Azotobacter* and Drobkov (1945, 1951) has shown that the effect on the development of root-nodule bacteria in legumes is similar. The relation of uranium to the growth of unicellular fungi has been studied by Kayser (1912) and Hoffmann (1943). According to Hoffmann, plants that have been killed by excessive amounts of uranium nitrate mold rapidly and densely, and it is suggested that uranium promotes the growth of mold fungus.

The effect of uranium and radiations from uranium on the germination of seeds has been studied experimentally by several workers. Stoklasa and Penkava conducted exhaustive germina-

tion experiments in 1928 and 1932 which we plan to duplicate in the laboratory in the near future. They found that growth is most stimulated by the addition of uranium nitrate to the nutrient solution in concentrations of 2 ppm uranium. In concentrations containing 47.6 ppm, poisoning effects are noticeable and a yellow color develops in the root tips; at 476 ppm, the roots are thin and yellow, and the leaves are twisted together. One per cent uranium is completely toxic to the germination of seeds. Stoklasa and Penkava also tested the effect of the alpha and gamma rays radiating from uranium by placing uranium nitrate in glass and lead tubes and found the effect to be consistently injurious. Others have reported on similar germination studies. Bequerel demonstrated in 1901 that long exposure to the radiation from radium prevented germination, and Verducci (1945) showed that radiations from uranium sulfate on seed germination were more severe than from uranium nitrate.

Excessive concentrations of uranium strongly inhibit root development in higher plants. Acqua (1912, 1913) and Bambacioni-Mezzeti (1934) have reported injury to the roots of plants absorbing uranium from solutions containing more than 50 ppm. According to Acqua, uranium is absorbed by the plant root and stored as a yellow deposit in the cell nuclei of the meristem, which results in a destruction of the chromatin and a cessation of nuclear activity. By this process the root prevents much of the uranium from entering the above-ground portion of the plant. Jacobson and Overstreet (1947) experimented with the radiation effects of a series of activated elements and demonstrated that radiation injury to the roots is severe with a mean activity of only 0.1 microcurie per gram of soil at the region of contact.

In the beneficial range of concentration, growth and maturing of the plant are accelerated. This phenomenon has been demonstrated by Stoklasa (1913), and Stoklasa and Penkava (1928, 1932), Gleditsch and Graf (1942) and Bevilotti (1945). Drobkov (1951) has shown by radiophotographs that uranium in the green portion of the plant migrates to those parts of the plant where development is most intensive—the growing tips, young leaves, seeds, and so forth; growth, flowering, fruiting, and ripening are stimulated; and the carbohydrate content is increased.

Physiologic studies of vanadium as a bio-element have accompanied those made of molybdenum. Bortels demonstrated that molybdenum is necessary to nitrogen-fixing bacteria (1930), that vanadium can be substituted for molybdenum to fulfill this requirement (1933), and that vanadium and molybdenum are necessary to higher plants in catalyzing nitrogen-fixation (1936). This work has been confirmed by Burk and Horner (1935), and Horner and others (1942, 1944). Suzuki (1903), Ducloux and Cobanera (1911-12), and G. Bertrand (1931) showed that small amounts of vanadium are stimulating to plant growth but that large amounts are toxic. Free and Trelease (1917) found 20 ppm vanadium toxic to wheat, and Brenchley (1932) 40 ppm toxic to barley. Gericke and von Rennenkampff (1939, 1940) and Gericke (1941) have shown that vanadium is more favorable for plant growth as an anion than as a cation.

The amounts of uranium and vanadium present in the soils associated with the carnotite deposits are commonly in the range that is retardative or even toxic to plant growth, and, as expected, the effects are noticeable in the field. Near mines, on dumps, and in poorly drained areas, plants have been observed to set fruit and to mature early in the season, with a marked reddening of the stem and seed and a yellowing of the leaves. The fine roots are commonly decayed and fragmental; the large roots frequently contain deposits of a greenish-yellow powdery material that has not yet been identified. Plants that are rooted in undrained pockets of soil containing a large percentage of soluble salts are dwarfed, exhibit frenching, and die before reaching maturity. The red and yellow coloration of the stems and leaves as described by Warington (1937), however, is possibly due to molybdenum, which occurs in large quantities in some of the sandstone beds.

Absorption of Ore Elements by Plants

The uranium ores of the Colorado Plateau contain not only uranium but also considerable quantities of vanadium and selenium. These elements are absorbed in unusual amounts by plants rooted in mineralized ground. Little information is available in the literature on the absorption of uranium in quantity by naturally growing plants, although experimental work is described by Baranov (1939) on the assimilation of this element

from nutrient solutions. In 1941 Hoffmann found 9 ppm U in a freshwater alga and began an investigation of the average content of uranium in plants (1942). In 1943 he reported fluorimetric determinations of uranium in the ash of various parts of plants. These determinations are similar in range to those made in the Trace Elements Laboratories of the U. S. Geological Survey and are given here.

Plant material	*Uranium* (ppm)
Apple seed	5.06
Grape stem	0.008
Grape skin	1.6
Grape seed	2800.0
Quackgrass leaves	0.179
Quackgrass root	0.573
Potato tuber	0.0318
Dill roots	1.54
Dill leaves	2.95
Dill seeds	0.956
Celery rootlets	7.91
Celery taproot	2.96
Celery root bark	0.039
Celery leaves	26.5
Garlic rootlets	41.07
Garlic bulb skin	4.38
Garlic bulblets	2.47
Mistletoe branch	3.73
Mistletoe leaves	5.25
Mistletoe berry	2.16
Mistletoe seed	6.78
Pine branches	0.425
Pine needles	2.54

Although his results are not consistent, perhaps owing to differences in the soil, they suggest that the uranium content of the seeds and roots may be higher than that of the leaves. Hoffmann also analyzed pear, apricot, and birch leaves in the spring and in the fall and found a consistent decrease in uranium content in the fall.

A much higher content of uranium has been reported by the Canada Department of Mines (informal communication from S. C. Robinson, Geological Survey of Canada, Ottawa, 1951) in plants growing in the vicinity of pitchblende deposits. Plants growing on the asphaltic sandstone deposits at Temple Mountain, Utah, and on limestone deposits at Grants, N. Mex., also absorb uranium readily (table 8). The maximum values are

considerably higher than those found in plants associated with carnotite deposits of the Colorado Plateau.

Ramirez (1914) studied the influence of vanadium on plant growth and concluded that vanadium is absorbed and stored by plants and as a result may show growth anomalies. However, no further work is reported on the vanadium content of plants until 1931 when Ter Meulen (1931) discovered unusual amounts of vanadium in a species of *Amanita*, a poisonous mushroom. D. Bertrand (1941, 1942, 1943) later analyzed fungi and 62 species of higher plants, which ranged in vanadium content from 0.152 to 4.2 ppm in the dry weight of leaves, 0.01 to 1.2 ppm in the roots, and had less than 0.01 ppm in the seeds. The average was 1 ppm in the dry weight of the plant or 7.1 ppm in the ash. Robinson and Edgington (1945) reported 20 ppm in the dry weight of several species.

Robinson (1933), Beath and others (1934), and Byers (1935) have shown that some plants in Wyoming, because of their selenium content, are poisonous to cattle. A considerable amount of selenium is also absorbed by vegetation growing on the Morrison formation of the Colorado Plateau. Some plants of the *Astragalus* group growing on the uranium deposits near Thompsons, Utah, were reported by Beath (1943) to accumulate up to 8,512 ppm selenium in the dry weight of the plant. The Trace Elements Laboratories of the U.S. Geological Survey have found 2,200 ppm selenium in the ash of similar plants from the same district. The analyses, however, were restricted to a few check samples.

The absorption of vanadium and more particularly uranium from sandstone deposits of the Colorado Plateau has been investigated by the Geological Survey in some detail. Analyses of uranium and vanadium from deposits near Thompsons, Utah, reported by Beath (1943) have been duplicated in the systematic analytical work of the study described in this report. Vegetation believed to be free of artificial contamination in mining areas averages 40 ppm V_2O_5 and 1.5 ppm uranium in the ash and contains maxima of 300 and 100 ppm, respectively, where rooted in ore.

All plants were air-dried, ground, and carefully ashed at about 500° C. The vanadium content was determined by an adaptation of the phospho-tungstate method. The uranium content was determined photofluorimetrically on a 5-mg sample of ash, using a mixed fluoride-carbonate flux to prepare the

phosphor. This method has recently been described by Grimaldi and others (1950). The limit of detection is about 1×10^{-9} gram uranium, using the instrument described by Fletcher and others (1950). The vanadium and uranium contents of the soils were determined by the same methods that were used for plants. It should be pointed out that only the total metal contents of the soils were determined and that the amount of these metals soluble in water and directly available to the plants in different types of soil is not known. The availability of these metals to plants is probably influenced by (1) the clay content, (2) the organic content, (3) the acidity of the soil, and (4) the combination in which the elements occur.

The amount of uranium and vanadium absorbed by plants varies with the species, time of year, part of plant, availability of these elements in the soil, and chemical composition of the country rock. The uranium content of species of plants growing on various materials and the uranium content of the underlying rocks are shown in table 1. The variation in uranium content of species growing on the same soil is shown horizontally, and that of a given species growing in different soils is shown vertically. The uranium content of any species growing in nonmineralized ground is rarely greater than 1 ppm. A content of 2 ppm or more is common in plants rooted in uranium-bearing rock. The V_2O_5 content of species of plants growing on various materials and the V_2O_5 content of the underlying rocks are shown in the same manner in table 2. Although excessive amounts of vanadium are sometimes absorbed when a large percentage of available vanadium is present around the roots, lesser variations are masked by the normally high requirements of the plant.

Table 3 shows the uranium and V_2O_5 content of various parts of several plants collected in mineralized areas.

Because uranium and vanadium are largely precipitated within the root near the point of intake, a root sampled at the surface will have a lower content of uranium and vanadium than the same root sampled in the ore-bearing sandstone, as shown in table 4. Contamination of the roots need not be considered because the roots contain more of these metals than the sandstone. Furthermore, as shown in table 3, the peeled roots contain more uranium and vanadium than the contaminated root bark.

TABLE 1
Uranium Content of Plants and Underlying Rocks*

	Formation	Material	Uranium in rocks (ppm)	Uranium in plant ash (ppm)														
				**Astragalus Pattersonii (milkvetch)	**Astragalus Preussii arctus (milkvetch)	**Astragalus confertiflorus	**Oryzopsis hymenoides (ricegrass)	Atriplex confertifolia (shadscale)	Atriplex canescens (saltbush)	Bahia nudicaulis	Chrysothamnus viscidiflorus (rabbitbrush)	Ephedra viridis (Mormon tea)	Artemisia spinescens (budsage)	Artemisia Bigelovii (sagebrush)	Haplopappus armerioides (goldenweed)	Fraxinus anomala (singleleaf ash)	Juniperus monosperma	Quercus Gambellii (scrub oak)
Mineralized	Salt Wash sandstone member of Morrison fm.	colluvium	3,070	..	..	..	..	3.0	..	8.0	7.0	..	..	..	..	..	..	..
		secondary oxide deposit	2,400	38.0	..	..	..	5.9	..	..	..	..	..	..	..	..	..	..
		shale	11	..	..	..	..	..	..	..	..	..	..	..	..	..	..	10.0
		shale	80	..	70.0	..	..	..	..	..	..	..	..	..	40.0	0.7	..	..
		sandstone	290	..	..	..	..	2.0	..	..	..	2.0	3.0	..	..	..	7.8	..
		sandstone	540	..	..	..	..	..	..									
		sandstone	20	..	..	..	30.0	..	..	..	..	..	..	..	..	..	..	..
		sandstone	400	..	..	..	..	..	..	..	..	..	..	..	..	..	2.0	..
Non-mineralized		sandstone (3 samples) (averaged)	3	..	..	..	..	0.2	..	..	0.6	1.0	..	0.87	..	0.5	0.1	0.5
	Dakota sandstone	sandstone	0.6	..	..	..	..	..	0.75	..	0.9	..	..	..	..	..	1.0	..
	Mancos shale	shale	4.0	..	..	0.8	..	..	..	..	..	..	..	..	..	..	..	..
		sandstone	0.9	..	..	..	..	0.26	0.68	..	..	..	..	..	..	..	0.0	..

* Ruth Kreher, Jesse Greene, and Norma Guttag, analysts. ** Selenium-indicator plants.

PLATE 1

Selenium-indicator Plants Common in Uranium Districts.

Fig. 1. *Oryzopsis hymenoides,* rice grass, in mine entrance.

Fig. 2. *Aster venusta,* woody aster.

Fig. 3. *Astragalus P. arctus,* milkvetch.

Fig. 4. *Astragalus Pattersonii,* milkvetch.

Fig. 5. *Stanleya pinnata,* Prince's Plume.

TABLE 2

V_2O_5 Content of Plants and Underlying Rocks*

	Formation	Material	V_2O_5 in rocks (ppm)	V_2O_5 in plant ash (ppm)														
				**Astragalus Pattersonii (milkvetch)	**Astragalus Preussii aretus (milkvetch)	**Astragalus conferti florus	**Oryzopsis hymenoides (ricegrass)	Atriplex confertifolia (shadscale)	Atriplex canescens (saltbush)	Bahia nudicaulis	Chrysothamnus viscidiflorus (rabbitbrush)	Ephedra viridis (Mormon tea)	Artemisia spinescens (budsage)	Artemisia Bigelovii (sagebrush)	Haplopappus armeriodes (goldenweed)	Fraxinus anomala (singleleaf ash)	Juniperus monosperma	Quercus Gambelii (scrub oak)
Mineralized	Salt Wash sandstone member of Morrison fm.	colluvium	180	..	..	..	..	10	..	70	200	..	..	..	..	..	..	..
		secondary oxide deposit ..	300	12	..	..	..	15	..	..	..	..	..	..	..	..	30	..
		shale	320	..	..	..	..	..	..	..	..	..	..	..	..	..	..	90
		shale	26,000	..	3,000	..	..	..	..	..	..	..	..	..	260	5	..	..
		sandstone	23,000	..	..	..	..	50	..	..	..	20	70	..	..	..	..	..
		sandstone	2,000	..	..	..	..	..	..	..	..	..	..	..	..	..	20	..
		sandstone	2,200	..	..	..	70	..	..	..	..	..	..	..	..	..	..	..
		sandstone	5,400	..	..	..	..	..	..	..	..	..	..	..	..	..	50	..
Non-mineralized		sandstone (3 samples) (averaged)....	216	..	..	..	..	90	..	..	50	50	..	70	..	5	10	5
	Dakota sandstone	sandstone	300	..	..	..	..	..	25	..	..	..	..	..	..	..	..	..
	Mancos shale	shale	180	..	..	90	..	60	30	..	..	..	..	..	..	..	..	..
		sandstone	1,200	..	..	..	..	..	..	..	..	..	..	..	..	..	60	..

* Ruth Kreher, Norma Guttag, and Jesse Greene, analysts. ** Selenium-indicator plants.

TABLE 3

Uranium and V_2O_5 Content of Various Parts of the Same Plant*

Plant	Uranium in ash (ppm)				V_2O_5 in ash (ppm)		
	Stems	Fruits	Tops	Roots	Fruit	Tops	Roots
Juniper		1	2	8	5	5	80
Juniper		0.6	2	2	5	40	70
Juniper		0.5	10	20	30	30	50
Juniper			3	5 (peeled)		20	70 (peeled)
				3 (bark)			30 (bark)
Saltbush	0.48	0.96	1.98 (leaves)				
Juniper	11 (peeled)		24 (washed)	49 (peeled)			
Pinyon	26 (peeled)		30 (washed)	74 (peeled)			

* Ruth Kreher, Jesse Greene, and Norma Guttag, analysts.

TABLE 4

Distribution of Uranium and V_2O_5 in Parts of a Juniper Tree and in Rock Underlying Plant*

	Uranium (ppm)	V_2O_5 (ppm)
Plant:		
Juniper tops (ash)	7.8	20
Juniper root (ash) at surface	8.4	200
Juniper root (ash) in mineralized sandstone at 4-foot depth	1,600	3,000
Rock underlying plant:		
Mineralized sandstone at 4-foot depth	540	2,000

* Ruth Kreher, Jesse Greene, and Norma Guttag, analysts.

A root on one side of a tree reaching into barren sandstone will not be of the same composition as one on the opposite side of the tree growing in mineralized rock. This variation is transmitted in a lesser degree to the tops and is illustrated in the analyses in table 5 of the end branches of a juniper tree.

TABLE 5

Uranium Content of Branches of Four Sides of a Juniper Tree Growing on East Side of an Ore Body*

	Uranium (ppm)
Juniper branches (ash), north side of tree	0.51
Juniper branches (ash), south side of tree	0.29
Juniper branches (ash), east side of tree	0.53
Juniper branches (ash), west side of tree	3.20

* Ruth Kreher, Jesse Greene, and Norma Guttag, analysts.

Analyses of samples taken in different months of the summer from the same trees indicate that the vanadium content rises during the growing season, and that the uranium content probably rises through the growing season in some evergreens but falls in most deciduous species. These findings agree with those of Hoffmann (1943).

Junipers and *Astragalus* are known to penetrate 20 to 30 feet of sandstone in some areas of the Colorado Plateau. The depth to which the roots penetrate depends not only on the species but also on water conditions and on the composition of

the rocks penetrated. Many desert plants or xerophytes possess deep-seated root systems that are able to draw water from moist beds at a considerable depth. Although the roots commonly penetrate to the water table, sufficient moisture may be retained in a sandstone bed above the water table to satisfy the requirements of the plant. The moisture content of the ore bed and of the intervening sandstone and shale beds is the prime controlling factor in the absorption of metals from ore bodies at depth. Tables 6 and 7 show analyses of plants and soils for U, V_2O_5, Se, MoO_3, and Pb. The samples were collected to show the relation of different species to various types of mineralized soil, the seasonal variations in content, and the relative variations of these elements and oxides in plant parts. In addition to samples taken in uranium districts, plant samples for comparative purposes were collected on nonmineralized parts of the Salt Wash sandstone member of the Morrison formation, and on the overlying Mancos shale and Dakota sandstone.

Quantitative differences in absorption by plants growing on shale and by those growing on sandstone are not great, as shown in tables 6 and 7. A more significant variation in absorption appears to be associated with differences in the amount of calcium in the ore. A rough comparison of the uranium, V_2O_5, and selenium contents of various types of ores from other districts is shown in table 8. Considerably more uranium is absorbed from the deposits of calcium-uranium carbonates and from deposits occurring in limestone than from calcium-poor sandstone and shale. The absorption of uranium from the carbonate mineral schroeckingerite by the plants at Wamsutter, Wyo., is particularly noteworthy and compares favorably with the absorption of the carbonate by plants in the Thompsons area. The absorption of uranium by plants is considerably greater from the asphaltic deposits of Temple Mountain, Utah, and the limestone deposits of Grants, N. Mex., than from the Colorado Plateau carnotite deposits studied. The variation may be due to the solubility of uranium and vanadium in each type of ore.

Artificial contamination of samples collected in areas of active mining introduces a source of error in comparative analysis (table 9). Dust from an operating surface pit may raise the uranium content of nearby trees from 2 to 100 ppm. Contamination from the Uravan mill has substantially increased

TABLE 6

Analyses of Plants Growing on Uranium-bearing Rocks and Soils of the Colorado Plateau 1949-50*

Locality and sample	Month sample collected	Ash (per cent)	U (ppm) Soil or rock	U (ppm) Plant ash	V_2O_5 (ppm) Soil or rock	V_2O_5 (ppm) Plant ash	Se (ppm) Plant ash	MoO_3 (ppm) Soil or rock	MoO_3 (ppm) Plant ash	Pb (ppm) Soil or rock	Pb (ppm) Plant ash
Sta. 1 Yellow Cat area, Thompsons district, Utah											
S. 2 Sandstone near carnotite ore	....	...	20	...	2,200	...	...	10	...	...	10
**P. 8 *Oryzopsis hymenoides*—tops	May	7.3	...	30	...	70	...	...	30	30	...
Oryzopsis hymenoides—roots	May	35.2	...	40	...	1,600	...	...	<10	...	30
S. 3 Surface soil 5 ft. above carnotite ore	....	...	2	...	180	...	...	<10	...	<10	...
S. 4 Shale layer in ore	....	...	290	...	23,000	...	...	20	...	30	...
P. 10 *Ephedra viridis*—tops	May	14.7	...	2	...	20	...	...	<10	...	10
P. 12 *Atriplex confertifolia*—tops	May	31.3	...	2	...	50	...	...	20	<10	...
P. 56 *Artemisia spinescens*—tops	May	18.4	...	3	...	70	...	...	<10	...	<10
Artemisia spinescens—roots	May	13.2	...	5	...	100	...	...	n.d.†	...	<10
Sta. 2 Yellow Cat area, Thompsons district, Utah											
S. 5 Sandstone ore at depth of 10 ft.	....	...	730	...	3,500	...	...	20	...	<10	...
S. 6 Shale layer containing roots	....	...	80	...	2,600	...	...	10	...	40	...
P. 14 *Fraxinus anomala*—leaves	May	7.8	...	0.7	...	5	...	...	10	...	40
Fraxinus anomala—leaves	Aug.	...	...	0.98	...	40	...	...	n.d.	...	n.d.
Fraxinus anomala—roots	May	5.4	...	9	...	30	...	...	10	...	110

* F. S. Grimaldi, Ruth Kreher, Claude Huffman, and F. N. Ward, chief analysts.
** Selenium-indicator plants.
† n.d. not determined.

TABLE 6 (Cont.)

Analyses of Plants Growing on Uranium-bearing Rocks and Soils of the Colorado Plateau 1949-50*

Locality and sample	Month sample Collected	Ash (per cent)	U (ppm) Soil or rock	U (ppm) Plant ash	V_2O_5 (ppm) Soil or rock	V_2O_5 (ppm) Plant ash	Se (ppm) Plant ash	MoO_3 (ppm) Soil or rock	MoO_3 (ppm) Plant ash	Pb (ppm) Soil or rock	Pb (ppm) Plant ash
Sta. 2 Yellow Cat area (cont.)											
S. 6 Shale layer containing roots (cont.)											
P. 16 *Haplopappus* sp.—tops	May	8.3	...	40	..	260	...	...	190	...	50
Haplopappus sp.—roots	May	14.7	...	20	...	180	...	...	160	...	30
**P. 18 *Astragalus Preussii arctus*	May	19	...	70	...	3,000	...	...	30	...	<10
Astragalus Preussii arctus—roots	May	5.8	...	70	...	2,600	...	...	70	...	<10
S. 7 Colluvium at base of cliff	....	...	7	...	180	70	...	10	...	<10	...
P. 20 *Bahia nudicaulis*—tops	May	20.9	...	8	...	180	...	...	10	...	<10
Bahia nudicaulis—roots	May	10.2	...	20	...	...	...	...	10	...	<10
P. 22 *Chrysothamnus viscidiflorus*—tops	May	17.3	...	7	...	200	...	...	30	...	<10
Chrysothamnus viscidiflorus—roots	May	16.8	...	10	...	200	...	...	80	...	**20**
P. 24 *Atriplex confertifolia*—tops	May	22	...	3	...	10	...	...	10	...	<10
Atriplex confertifolia—roots	May	13.8	...	5	...	90	...	...	<10	...	<10
Sta. 3 Yellow Cat area, Thompsons district, Utah											
S. 8 Clay layer containing roots at 1-ft depth	...	...	3	...	320	...	...	10	...	10	20
P. 26 *Quercus Gambellii*—leaves	May	4.0	...	10	...	90	...	...	20	...	20
Quercus Gambellii—leaves	Aug.	...	...	40	...	200	...	...	n.d.	...	n.d.
Quercus Gambellii—roots	May	10.8	...	190	...	1,700	...	...	20	...	10

* F. S. Grimaldi, Ruth Kreher, Claude Huffman, and F. N. Ward, chief analysts.

** Selenium-indicator plants.

TABLE 6 (Cont.)

Analyses of Plants Growing on Uranium-bearing Rocks and Soils of the Colorado Plateau 1949-50*

Locality and sample	Month sample collected	Ash (per cent)	U (ppm) Soil or rock	U (ppm) Plant ash	V_2O_5 (ppm) Soil or rock	V_2O_5 (ppm) Plant ash	Se (ppm) Plant ash	MoO_3 (ppm) Soil or rock	MoO_3 (ppm) Plant ash	Pb (ppm) Soil or rock	Pb (ppm) Plant ash
Sta. 1. McCoy-Flattop area, Thompsons district, Utah											
S. 106 Uranium carbonate in mudstone	...	...	2,400	...	300	...	...	n.d.	...	n.d.	...
**P. 636 *Astrogalus Pattersonii*—tops	July	11.6	...	38	...	12	1,280	...	150	...	20
P. 637 *Atriplex confertifolia*—tops	July	22.8	...	5.9	...	15	1,260	...	150	...	<20
S. 108 Altered mudstone in Windy Point rim	...	...	20	...	800	...	...	n.d.	...	n.d.	...
**P. 640 *Astragalus Preussii arctus*—tops	July	9.0	...	20	...	14	110	...	60	...	20
Sta. 2. McCoy-Flattop area, Thompsons district, Utah											
S. 18 Carnotite ore at 18-ft. depth containing roots	...	...	57	...	3,000	...	...	6	...	...	...
P. 214 *Juniperus monosperma* roots (collected in mine)	July	5.5	...	7.4	...	80	...	...	15	...	...
Sta. 3 McCoy-Flattop area, Thompsons district, Utah											
S. 19 Surface soil	...	...	3.1	...	100	...	...	n.d.	...	n.d.	...
S. 20 Ore at 9 ft. in which roots are imbedded	...	...	440	...	5,400	...	...	n.d.	...	n.d.	...
P. 38 *Juniperus monosperma* tops	May	4.9	...	2	...	50	...	...	40	...	80
Juniperus monosperma—in mine—roots	May	6.5	...	20	...	140	...	...	30	...	10
Juniperus monosperma—in mine—roots	July	...	...	140	...	4,000	...	...	130	...	...
Juniperus monosperma—berries	May	4.7	...	0.2	...	5	...	...	10	...	<10

* F. S. Grimaldi, Ruth Kreher, Claude Huffman, and F. N. Ward, chief analysts.

** Selenium-indicator plants.

TABLE 6 (Cont.)

Analyses of Plants Growing on Uranium-bearing Rocks and Soils of the Colorado Plateau 1949-50*

Locality and sample	Month sample collected	Ash (per cent)	U (ppm) Soil or rock	U (ppm) Plant ash	V_2O_5 (ppm) Soil or rock	V_2O_5 (ppm) Plant ash	Se (ppm) Plant ash	MoO_3 (ppm) Soil or rock	MoO_3 (ppm) Plant ash	Pb (ppm) Soil or rock	Pb (ppm) Plant ash
Sta. 4 McCoy-Flattop area, Thompsons district, Utah											
S. 22 Ore at 4-ft. depth containing roots	...	...	540	...	2,000	...	...	n.d.	...	...	...
P. 217 *Juniperus monosperma* tops	July	5.0	...	7.8	...	20	...	...	24	...	...
Juniperus monosperma—surface roots	July	2.5	...	8.4	...	200	...	...	30	...	...
Juniperus monosperma—in mine—roots	July	...	...	1,600	...	3,000	...	...	15	...	...
Sta. 7. McCoy-Flattop area, Thompsons district, Utah											
S. 28 Surface soil (carnotite ore at 10-ft. depth)	...	...	170	...	800	...	14.0	...	...	...	...
**P. 223 *Oryzopsis hymenoides* tops	July	3.9	...	82	...	200	...	...	...	...	...

* F. S. Grimaldi, Ruth Kreher, Claude Huffman, and F. N. Ward, chief analysts.

** Selenium-indicator plants.

TABLE 7

Analyses of Plants Growing on Non-mineralized Rocks and Soils of the Colorado Plateau*

Locality and sample	Month sample collected	Ash (per cent)	U (ppm)		V_2O_5 (ppm)		Se (ppm)	MoO_3 (ppm)		Pb (ppm)	
			Soil or rock	Plant ash	Soil or rock	Plant ash	Soil or rock	Soil or rock	Plant ash	Soil or rock	Plant ash
Sta. 5 Yellow Cat area, Thompsons district, Utah											
S. 11 Surface soil over nonmineralized (?) Salt Wash ss mem. of Morrison formation	.....	....	1	....	220	...	...	<10	...	<10	...
P. 49 *Juniperus monosperma* tops	May	5.3	...	2	...	40	...	...	<10	...	<10
Juniperus monosperma tops	Aug.	....	...	0.1	...	10	...	...	n.d.†	...	n.d.
Juniperus monosperma roots	May	17.2	...	2	...	70	...	...	<10	...	40
Juniperus monosperma berries	May	5.2	...	0.6	...	5	...	...	10	...	<10
Juniperus monosperma berries	Aug.	....	...	0.04	...	30	...	...	n.d.	...	n.d.
P. 52 *Fraxinus anomala* tops	May	8.4	...	0.5	...	5	...	...	<10	...	10
Fraxinus anomala tops	Aug.	....	...	<0.01	...	30	...	...	n.d.	...	n.d.
Fraxinus anomala roots	May	4.8	...	1	...	30	...	...	<10	...	10
P. 54 *Artemisia Bigelovii* tops	May	9.7	...	2	...	50	...	...	10	...	<10
Artemisia Bigelovii tops	Aug.	....	...	0.87	...	70	...	...	n.d.	...	n.d.
Artemisia Bigelovii roots	May	11.3	...	2	...	5	...	...	<10	...	30
Sta. 6 Yellow Cat area, Thomsons district, Utah											
S. 13 Surface soil over nonmineralized (?) Salt Wash ss mem. of Morrison formation	.....	....	6	....	200	...	...	<10	...	10	...
P. 67 *Ephedra viridis* tops	May	12.5	...	1	...	50	...	...	<10	...	20
Ephedra viridis roots	May	8.1	...	1	...	50	...	...	<10	...	40
P. 69 *Chrysothamnus viscidiflorus* tops	May	11.7	...	0.6	...	50	...	...	10	...	40
Chrysothamnus viscidiflorus roots	May	14.7	...	1	...	30	...	...	<10	...	30
P. 71 *Atriplex confertifolia* tops	May	34.3	...	0.2	...	90	...	...	<10	...	<10
Atriplex confertifolia roots	May	10.6	...	0.2	...	50	...	...	10	...	40

* F. S. Grimaldi, Ruth Kreher, Claude Huffman, and F. N. Ward, chief analysts.

† n.d. not determined.

TABLE 7 (Cont.)

Analyses of Plants Growing on Non-mineralized Rocks and Soils of the Colorado Plateau*

Locality and sample	Month sample collected	Ash (per cent)	U (ppm)		V_2O_5 (ppm)		Se (ppm)	MoO_3 (ppm)		Pb (ppm)	
			Soil or rock	Plant ash	Soil or rock	Plant ash	Soil or rock	Soil or rock	Plant ash	Soil or rock	Plant ash
Sta. 7 Yellow Cat area, Thompsons district, Utah											
S. 12 Surface soil over nonmineralized (?) Salt Wash	.....	....	2	....	230	...	...	<10	...	10	...
P. 58 *Quercus Gambellii* tops	May	4.3	...	0.5	...	5	...	...	<10	...	10
Quercus Gambellii roots	May	12.3	...	2	...	50	...	...	<10	...	<10
Sta. 1 Mancos shale 10 miles east of Thompsons, Utah											
S. 14 Surface soil	.....	....	4	....	180	...	...	<10	...	<10	...
**P. 73 *Astragalus confertiflorus* tops	May	14.7	...	0.8	...	90	...	...	50	...	20
Astragalus confertiflorus roots	May	18.8	...	30	...	70	...	...	120	...	<10
Mancos shale 40 miles east of Thompsons, Utah, along Highway 50											
Sta. 1 450 ft. north of highway											
P. 1 *Atriplex canescens* tops	Aug.	15	...	1	...	30	...	...	60	...	...
P. 2 *Atriplex confertifolia* tops	Aug.	30	...	0.04	...	60	...	...	30	...	...
P. 3 *Juniperus monosperma* tops	Aug.	4.5	...	1.1	...	60	...	...	15	...	...
P. 4 *Sarcobatus vermiculatus* tops	Aug.	27.5	...	0.15	...	20	...	...	30	...	...

* F. S. Grimaldi, Ruth Kreher, Claude Huffman, and F. N. Ward, chief analysts.

** Selenium-indicator plants.

TABLE 7 (Cont.)

Analyses of Plants Growing on Non-mineralized Rocks and Soils of the Colorado Plateau*

Locality and sample	Month sample collected	Ash (per cent)	U (ppm) Soil or rock	U (ppm) Plant ash	V_2O_5 (ppm) Soil or rock	V_2O_5 (ppm) Plant ash	Sc (ppm) Soil or rock	MoO_3 (ppm) Soil or rock	MoO_3 (ppm) Plant ash	Pb (ppm) Soil or rock	Pb (ppm) Plant ash
Sta. 2 70 ft. northwest of Sta. 1											
P. 5 *Atriplex canescens* leaves	Aug.	15	...	0.12	...	20	...	...	15	...	...
P. 6 *Atriplex confertifolia* leaves	Aug.	30	...	0.10	...	40	...	...	30	...	...
P. 7 *Juniperus monosperma* tops	Aug.	5	...	0.01	...	50	...	...	15	...	...
P. 8 *Sarcobatus vermiculatus* tops	Aug.	26	...	0.17	...	10	...	...	30	...	...
Sta. 3 210 ft. north of highway											
S. 1 Surface soil	.....	....	0.9	...	1,200	...	<0.7	n.d.	...	2.0	...
P. 9 *Atriplex canescens* leaves	Aug.	15	...	0.68	...	<10	...	...	30	...	...
P. 10 *Atriplex confertifolia* leaves	Aug.	33	...	0.26	...	40	...	...	15	...	...
P. 11 *Juniperus monosperma* tops	Aug.	5	...	0.01	...	40	...	...	30	...	...
P. 12 *Sarcobatus vermiculatus* leaves	Aug.	25	...	0.19	...	20	...	...	30	...	...
Sta. 1 Dakota sandstone, Harley Dome, Utah											
S. 20 Sandstone residuum	.....	....	0.6	....	300	...	<0.7	n.d.	...	1.0	...
P. 20 *Juniperus monosperma* tops	July	4	...	1	...	30	...	...	10	...	20
P. 21 *Chrysothamnus viscidiflorus* tops	July	7.6	...	0.9	...	n.d.	...	...	10	...	20
P. 22 *Atriplex canescens* tops	July	14.4	...	0.75	...	25	...	...	10	...	20

* F. S. Grimaldi, Ruth Kreher, Claude Huffman, and F. N. Ward, chief analysts.

TABLE 8

Comparative Collections from Other Uranium Districts*

Locality and sample	Ash (per cent)	U (ppm) Soil or rock	U (ppm) Plant ash	V_2O_5 (ppm) Soil or rock	V_2O_5 (ppm) Plant ash	Se (ppm) Soil or rock	Se (ppm) Plant ash	P_2O_5 (per cent) Soil or rock	P_2O_5 (per cent) Plant ash
Wamsutter, Wyoming									
Uranium carbonate in alluvium	....	270	.....	100	.....	.....	.....	.....	.....
Sarcobatus vermiculatus, greasewood tops	25.0	.....	14	.....	0	.....	.....	.....	.....
Sarcobatus vermiculatus, greasewood roots	....	.....	7,400	.....	400	.....	.....	.....	.....
Black muck from mineralized spring	....	10	.....	40	.....	.....	.....	.....	.....
Eleocharis palustris, spikerush tops	....	.....	1.7	.....	0	.....	.....	.....	.....
Spirogyra-type algae	....	.....	39	.....	500	.....	.....	.....	.....
Uraniferous lignite bed	....	20	.....	1,500	.....	2	.....	.....	.....
****Stanleya arcuata*, Prince's Plume tops	15.0	.....	0.6	.....	65	.....	15	.....	.....
Uraniferous lignite bed	....	50	.....	400	.....	2	.....	.....	.....
Cleome integrifolia angusta tops	5.3	.....	1.2	.....	70	.....	<1	.....	.....
Marysvale, Utah									
Kaolinized vein deposit	....	1,000	.....	600	.....	0.8	.....	.....	.....
Atriplex confertifolia, shadscale tops	23.0	.....	4.8	.....	n.d.†	.....	n.d.	.....	.....
Juniperus monosperma tops	4.0	.....	0.7	.....	n.d.	.....	n.d.	.....	.....
Temple Mountain, Utah									
Asphaltic ss. ore, Shinarump conglomerate	....	760	.....	1,500	.....	0.8	.....	.....	.....
Wood in ore	....	4,900	.....	7,800	.....	3.0	.....	.....	.....
Juniperus monosperma tops	4.0	.....	66	.....	350	.....	n.d.	.....	.....
Juniperus monosperma tops	4.0	.....	100	.....	470	.....	n.d.	.....	.....
****Oryzopsis hymenoides*, Indian ricegrass tops	5.5	.....	20	.....	260	.....	10	.....	.....
****Stanleya pinnata*, Prince's Plume tops	10.0	.....	37	.....	120	.....	190	.....	.....

* Claude Huffman, J. W. Harbaugh, R. G. Havens, and Ruth Kreher, analysts.

** Selenium-indicator plants.

† n.d. not determined.

TABLE 8 (Cont.)

Comparative Collections from Other Uranium Districts*

Locality and sample	Ash (per cent)	U (ppm) Soil or rock	U (ppm) Plant ash	V_2O_5 (ppm) Soil or rock	V_2O_5 (ppm) Plant ash	Se (ppm) Soil or rock	Se (ppm) Plant ash	P_2O_5 (per cent) Soil or rock	P_2O_5 (per cent) Plant ash
Buck Creek, Wyoming									
Phosphate rock in shale, Phosphoria formation	....	120	.....	3,600	.....	46.0	.....	9.0	.....
Apocynum androsaemifolium, dogbane tops	9.0	.....	0.45	.....	n.d.	.....	n.d.	.....	1.10
Smilacena stellata, wild spikenard tops	10.0	.....	0.25	.....	n.d.	.....	n.d.	.....	1.30
Cokeville, Wyoming									
Phosphate rock in shale, Phosphoria formation	....	210	.....	5,600	.....	12	.....	28.0	.....
****Oryzopsis hymenoides**, ricegrass tops	8.0	.....	4.3	.....	690	.....	<1.0	.....	0.18
Phosphate rock with fluorine	....	60	.....	2,400	.....	4	.....	31.0	.....
Artemisia tridentata, sagebrush tops	5.0	.....	1.8	.....	150	.....	15.0	.....	0.65
Calciferous shale	....	20	.....	800	.....	52	.....	1.3	.....
Chrysothamnus parryi, rabbitbrush tops	6.0	.....	1.0	.....	93	.....	n.d.	.....	0.58
Vanadiferous mudstone	....	20	.....	6,200	.....	96	.....	2.0	.....
Artemisia tridentata, sagebrush tops	5.0	.....	0.75	.....	110	.....	n.d.	.....	0.65
Grants, New Mexico									
Tyuyamunite in Todilto limestone	....	2,200	.....	3,900	.....	<0.01	.....	.....	.....
Pinus edulis, pinyon washed tops	2.3	.....	33	.....	<10	.....	.....	.....	.....
Juniperus monosperma, washed tops	3.6	.....	49	.....	<10	.....	.....	.....	.....

* Claude Huffman, J. W. Harbaugh, R. G. Havens, and Ruth Kreher, analysts.

** Selenium-indicator plants.

the content of uranium in juniper ash near the Club mine, 1 mile south of the mill at Uravan, Colo. Samples collected between the Club mine and the mill show an increment of more than 1,000 ppm uranium, as seen in table 10.

TABLE 9

Contamination of Trees near Area of Mining*

Plant	Ash (per cent)	Uranium (ppm in ash)	V_2O_5 (ppm in ash)
Cowania mexicana			
During active mining 1949	5.3	51.0	400.0
During dormant period 1950, unwashed sample	5.0	8.4	75.0
During dormant period 1950, washed sample	5.0	6.4	50.0
Juniperus monosperma			
Sampled in 1949	5.0	7.8	20.0
Sampled in 1950, unwashed sample	4.5	7.0	65.0
washed sample	4.5	5.3	50.0

*Claude Huffman and Ruth Kreher, analysts.

TABLE 10

Contamination of Junipers Near a Uranium Mill*

Distance from mill	Number of samples	Uranium content (ppm)
2,000-4,000 ft.	6	40 (average)
800-1,500 ft.	4	150 (average)
Adjacent to the mill	2	700 and 1,100

*Claude Huffman, analyst.

The need for guarding against the collection of contaminated plants in any sampling program cannot be emphasized too strongly. A routine should be established of checking surface soil and washing occasional plant samples to assure representative analyses. Because the extent of contamination in active areas was not realized during the preliminary sampling for basic information, many of the early Survey analyses have been rejected. Tables 6 and 7, however, summarize data on samples collected in inactive areas, where contamination is probably at a minimum.

Indicator Plants

Although an indicator plant has been defined by agricultural specialists as a plant that is restricted in distribution to soils containing unusually large quantities of a particular element, a plant can be used as an indicator in geochemical prospecting if its distribution is controlled by any factor related to the chemistry of the ore deposit. A plant can indicate mineralized ground by either its presence or its absence; it may or may not accumulate the element being sought; and, in different chemical environments, it can indicate various metallic deposits. No specific indicator plants of either uranium or vanadium are mentioned in the literature. The association of selenium-indicator plants with carnotite deposits near Thompsons, Utah, however, was early noticed by Beath (1943) of the University of Wyoming, and a major objective of the Geological Survey work in this area has been to establish the use of selenium-indicator plants as a method of prospecting.

Studies have also been made of the plants in the Thompsons and other uranium districts to determine the tolerance of various plant species for highly mineralized soils. The ecology of 13 mineralized and 11 nonmineralized areas has been studied in detail in the Thompsons district. In each area complete collections were made on a strip of ground 5 feet wide and 10 feet long directly over a mine entrance or a known ore body. In each place the ore was not more than 15 feet below the surface and in most places was less than 10 feet. A study was made at the same time of the ecology of the dumps and colluvium along the base of the ore outcrop. To compare the resulting lists of plants with plants growing on nonmineralized ground, similar collections were made wherever possible on the same outcrop at a distance of about 500 feet from the deposit. It should be noted that the studies of plants growing on nonmineralized ground were all made *within* the uranium district, so that the difference is one of degree and is not as marked as if the studies had been made in an entirely barren region.

The flora of uranium-tolerant plants compiled from these lists is given in table 11. The commonest of these plants throughout the district are rabbitbrush, shadscale, mormon tea, milkvetch, and grasses, but junipers, scrub oak, serviceberry, and cliffrose are common on some of the higher mesas. The floral

assemblage over ore is characterized particularly by the presence of the selenium-indicator plants and the replacement of *Atriplex canescens*, the common narrow-leafed saltbush, by the shadscale saltbush, *Atriplex confertifolia*. This change in saltbush species in uranium districts has not previously been recognized. Although *A. canescens* is a selenium absorber, the plant apparently cannot tolerate the increase in salt content in mineralized soil. The change from the narrow-leafed desert shrub to the wider-leafed shadscale affects the appearance of the vegetation in a uranium district to a remarkable degree, and this appearance is probably subconsciously used by many prospectors. The plants unable to grow over shallow uranium deposits are likewise shown in table 11. Sagebrush and *Grayia* are especially intolerant and their absence in some places can be as useful in prospecting as positive indicators.

Chemical analyses of channel samples taken through carnotite ore bodies and enclosing barren sandstones of the Salt Wash member of the Morrison formation show a close association of selenium and sulfur with uranium and vanadium in these deposits. A logical corollary of the geologic association of selenium with the uranium ores is the affinity of selenium-indicator plants for carnotite deposits. The various species have distinct distribution patterns and have been mapped and studied separately. Of these, woody aster and ricegrass are common on alluvium and dune sand throughout the uranium districts. Their prevalence is indicated in tables 8 and 11.

Astragalus confertiflorus, a milkvetch with bluish finely divided foliage, grows on outcrops of blue mudstone, from which it extracts selenium and considerable ferrous iron. According to Trelease and Beath (1949, p. 155) a very low percentage of the selenium absorbed by this plant is water soluble. It is possible that the insoluble fraction is bound with iron. The species is replaced by *Astragalus Preussii var. arctus* where the mudstones contain excessive amounts of selenium.

Astragalus P. arctus and closely related *Astragalus Pattersonii* are the most useful indicator plants of carnotite deposits on the Colorado Plateau. They both absorb large quantities of soluble selenium and are found in conspicuous stands along the base of the ore-bearing sandstone, on the blue mudstone at the base of the sandstone, and, where there is sufficient moisture, on sandstone outcrops above the ore. Patches of these

TABLE 11

Ecological Variations in the Desert Flora of the Thompsons District, Grand County, Utah; Compiled from a Study of 24 Areas[1]

	Common name	Number of mineralized areas, out of 13 examined, in which species were observed	Number of nonmineralized areas, out of 11 examined, in which species were observed
Flora tolerant of mineralized ground*			
Grasses:			
Graminae:			
Aristida Fendleriana Steud.	fendler three-awn	10	9
Bromus tectorum L.	cheatgrass	12	11
Elymus salina Jones	wild rye	8	7
Hilaria jamesii (Torr.) Benth.	galleta	11	9
***Oryzopsis hymenoides* (R. & S.) Ricker	Indian ricegrass	12	6
Sitanion hystrix (Nutt.) Smith	squirreltail	4	5
Stipa comata Trin. & Rupr.	needlegrass	2	0
Trees and shrubs:			
Ephedraceae:			
Ephedra trifurca Torr.	mormon tea	9	11
Pinaceae:			
Juniperus monosperma (Engelm.) Rydb.	oneseed juniper	5	4
Fagaceae:			
Quercus Gambellii Nutt.	Gambel's oak	2	1
Chenopodiaceae:			
Atriplex confertifolia (T. & F.) S. Wats.	shadscale	13	9

* *Pinus edulis*, pinyon, is also uranium-tolerant but occurs only at higher altitudes.

** Selenium-indicator plants.

[1] Plants collected by R. Stillman and Mary Durrell. Identifications checked by A. Holmgren of Utah State Agricultural College.

TABLE 11 (Cont.)

Ecological Variations in the Desert Flora of the Thompsons District, Grand County, Utah; Compiled from a Study of 24 Areas[1]

	Common name	Number of mineralized areas, out of 13 examined, in which species were observed	Number of nonmineralized areas, out of 11 examined, in which species were observed
Flora tolerant of mineralized ground			
Trees and shrubs: (continued)			
Rosaceae:			
Amelanchier utahensis Koehen.	serviceberry	1	0
Coleogyne ramosissima Torr.	blackbrush	6	6
Cowania mexicana Don.	cliffrose ("vanadium bush")	2	0
Oleaceae:			
Fraxinus anomala Torr.	singleleaf ash	1	1
Compositae:			
Tetradymia spinosa H. & P.	tetradymia	3	2
Browse:			
Liliaceae:			
Calachortus Nuttali Torr. & Gray	Mariposa lily	2	0
Polygonaceae:			
Erigonum inflatum Torr.	desert trumpet	4	2
Erigonum bicolor Torr.	Erigonum	1	0
Cruciferae:			
***Stanleya pinnata* Greene	Prince's Plume	1	0
Lepidium lasciocarpum A. Gray	peppergrass	2	1
Lepidium montanum Nutt.	peppergrass	6	7

** Selenium-indicator plants.

[1] Plants collected by R. Stillman and Mary Durrell. Identifications checked by A. Holmgren of Utah State Agricultural College.

TABLE 11 (Cont.)

Ecological Variations in the Desert Flora of the Thompsons District, Grand County, Utah; Compiled from a Study of 24 Areas[1]

	Common name	Number of mineralized areas, out of 13 examined, in which species were observed	Number of nonmineralized areas, out of 11 examined, in which species were observed
Flora tolerant of mineralized ground			
Browse: (continued)			
Leguminosae:			
***Astragalus Preussii var. arctus* Jones	milkvetch	10	2
***Astragalus Thompsonae* Rydb.	milkvetch	5	1
***Astragalus Pattersonii* A. Gray	milkvetch	2	0
Polemoniacete:			
Gilia pungens Benth.	gilia	4	4
Gilia congesta (A. Gray) Rydb.	gilia	1	0
Boraginaceae:			
Cryptantha flava (A. Nels.) Payson	cryptanthe	4	0
Euphorbiaceae:			
Euphorbia typica Rydb.	sand spurge	6	5
Plantaginaceae:			
Plantago Purshii R. & S.	woolly Indianwheat	1	1
Compositae:			
***Aster venustra* Rydb.	woody aster	6	5
Solidago Petridoria Blake	goldenrod	4	4

** Selenium-indicator plants.

[1] Plants collected by R. Stillman and Mary Durrell. Identifications checked by A. Holmgren of Utah State Agricultural College.

TABLE 11 (Cont.)

Ecological Variations in the Desert Flora of the Thompsons District, Grand County, Utah; Compiled from a Study of 24 Areas[1]

	Common name	Number of mineralized areas, out of 13 examined, in which species were observed	Number of nonmineralized areas, out of 11 examined, in which species were observed
Flora tolerant of mineralized ground			
Browse: (continued)			
Artemisia spinescens D. C. Eat	bud-sage	1	1
Grindelia squarrosa (Pursh) Dunal.	gumweed	2	0
Senecio uintahensis (A. Nels.) Greene	ragwort	1	0
Haplopappus armeroides	goldenweed	3	0
Gutierrezia divaricata (Nutt) T. & G.	turpentine weed	12	11
Flora intolerant of mineralized ground			
Shrubs:			
Chenipodiaceae:			
Atriplex canescens James	fourwing saltbush	0	4
Grayia Brandegei A. Gray	hop-sage	0	3
Compositiae:			
Artemisia Bigelovii A. Gray	sagebrush	2	6
Browse:			
Scrophulariaceae;			
Castilleja angustifolia (Nutt.) G. Don.	paintbrush	0	2
Compositae;			
Bahia nudicaulis A. Gray	Bahia	1	4

[1] Plants collected by R. Stillman and Mary Durrell. Identifications checked by A. Holmgren of Utah State Agricultural College.

plants indicate selenium and possibly uranium in a nearby sandstone bed. The ore may be as much as 50 feet beneath the ground surface. These species of *Astragalus* are limited by altitude and are not found on the Plateau much above 6,000 feet.

Stanleya pinnata or Prince's Plume, a tall yellow crucifer with a spike of conspicuous flowers, also requires considerable selenium. Unlike the *Astragalus* species, *Stanleya* is not limited by altitude; but it requires sulfur in addition to selenium, and access to larger amounts of water. These differences vary the patterns of distribution of the two genera considerably. *Astragalus* is commonest in low, hot, dry areas of the Colorado Plateau, and *Stanleya* is commonest near gypsiferous deposits at any altitude in areas of discharge or where the roots are in reach of ground water.

Other members of the lily and mustard families that accumulate sulfur grow around the deposits and can be used as indicators under favorable circumstances. For instance, *Sisymbrium altissimum* is abundant around deposits of the Spud Patch and Charles T groups in San Miguel County, Colo., at an altitude higher than that of the *Astragalus* species. *Eriogonum inflatum* is also common on high-sulfate soils and grows around uranium deposits that contain gypsum.

Useful indicator plants and their observed occurrence are shown in table 12. To augment the information on distribution of these various indicator plants gained from studies of carnotite deposits, reconnaissance studies were made of other types of uranium deposits in the Western States. The same suite of selenium accumulators was observed in the same ecological position on the uranium deposits of the sandstone of the Shinarump conglomerate at Temple Mountain, Utah. *Stanleya pinnata* is an indicator of uraniferous lignites near Wamsutter, Wyo. Ricegrass and other indicator plants requiring less than 1 ppm of selenium are present on the altered hydrothermal deposits of Marysvale, Utah, and on shales of the Phosphoria formation of Idaho and Wyoming. Sulfur indicators, however, are more prevalent than selenium indicators on the deposits of the Phosphoria formation in Idaho and Wyoming.

CONCLUSIONS

The relation of plants to uranium deposits of the Colorado Plateau has been studied over a period of two years. Three

TABLE 12
Indicator Plants Useful over Uranium Deposits

| Plant | Element indicated | URANIUM | | |

separate lines of investigation have been followed: the observable effects of mineralized soil on growth habits; the absorption of uranium and associated ore elements by plants; and the ecologic distribution of plants around the ore deposits. Physiologic symptoms of ill health are observed mainly on dumps and disturbed ground, where the ore metals have become soluble and available during weathering. Symptoms of uranium poisoning are masked by the excessive amounts of vanadium, selenium, and molybdenum present in the ore. Plants absorb considerable uranium and vanadium through the roots and some is transferred to the twigs and leaves, where it can be detected by chemical analyses. The leaves of plants that are rooted in ore contain 2 to 100 ppm uranium and 40 to 200 ppm V_2O_5. The normal background content of plants collected from barren sandstone and shale is less than 1 ppm uranium and 20 to 40 ppm V_2O_5. Selenium and sulfur accumulators can be used as indicators of uranium ore under the proper circumstances. The distribution of selenium indicators near Thompsons, Utah, has been studied in detail and the distribution patterns for the various species have been determined. The same species occur on other types of uranium deposits in the Western States.

References

Agulhon, H., and Sazerac, R., 1913. The effect of uranium salts and metallic uranium on *Bacillus pyocyaneus*: Chem. Zentralbl., vol. 84, pp. 830; Acad. sci. Paris Comptes rendus, vol. 156, pp. 162-164.

———, and Robert, Th., 1914. The effect of colloidal uranium on *Bacillus pyocyaneus*: Acad. sci. Paris Comptes rendus, vol. 158, pp. 349-352.

Acqua, C., 1912. The action of uranium on the vegetable cell: Arch. farmacol. sper., vol. 14, no. 2, pp. 81-84.

———, 1913. Nuclear degeneration produced by uranium in the plant cell: R. accad. Lincei e Sci., Rendus, vol. 22, pp. 390-392.

Aso, K., 1903. Can thorium and cerium exert any stimulating action on phanerogamous plants: Tokyo Coll. Agr. Bull., vol. 6, pp. 143-146.

Bambacioni-Mezzetti, V., 1934. Action of uranium chloride and of gamma-rays on the geotropical sensibility of roots: Soc. italiana progresso sci. Atti, vol. 22, no. 3, pp. 56-57.

Baranov, V. I., 1939. Assimilation of radioactive elements by plants: Acad. sci. U.R.S.S. Comptes rendus 24, pp. 951-954.

Beath, O. A., 1943. Toxic vegetation growing on the Salt Wash sandstone member of the Morrison formation: Jour. Botany, vol. 30, pp. 698-707.

———, Draize, J. H., Eppson, H. F., and others, 1934. Certain poisonous plants of Wyoming activated by selenium and their association with respect to soil types: Am. Pharm. Assoc. Jour., vol. 23, pp. 94-97.

Bequerel, H., 1901. On the chemical effects from radiations of radium: Acad. sci. Paris Comptes rendus, vol. 133, pp. 709-712.

———, 1913. The influence of uranium and thorium salts on the development of tuberculosis *Bacillus*: Acad. sci. Paris Comptes rendus, vol. 156, p. 164; Chem. Zentralbl., vol. 84 (Pt. I), p. 830.

Bertrand, Didier, 1941. Vanadium in plants: Soc. chim. biol. Bull., vol. 23, pp. 391-397.

———, 1942. Distribution of vanadium in plants: Soc. chim. Paris Bull., ser. 5, vol. 9, pp. 121-133.

———, 1943. Vanadium in fungi, especially *Amanita*: Soc. chim. biol. Bull., vol. 25, pp. 194-197.

Bertrand, Gabriel, 1931. On the physiological significance of manganese and other trace elements found in organisms: Zeitschr. angew. Chemie, vol. 44, pp. 917-921.

Bevilotti, V., 1945. Biological action of radioactive substances VI. Action of uranium on the germination of vegetable seeds: Soc. italiana biol. sper. Boll., vol. 20, pp. 558-559.

Bortels, Hermann, 1930. Molybdenum as a catalyzer in biological nitrogen-fixation: Arch. Mikrobiol., vol. 1, pp. 333-342.

———, 1933. A short report on the catalysis of organic nitrogen-fixation: Zentralbl. Bakt., Abt. II, vol. 87, pp. 476-477.

———, 1936. Further studies on the significance of molybdenum, vanadium, tungsten, and other soil materials on N-fixing and other organisms: Zentralbl. Bakt. Parasitenk., Abt. II, vol. 95, pp. 193-217.

Brenchley, Winifred E, 1932. The action on the growth of crops of small percentages of certain metallic compounds when applied wth ordinary artificial fertilizers: Jour. Agr. Sci., vol. 22, pp. 704-735.

Burk, D., and Horner, C. 1935. The specific catalytic role of molybdenum and vanadium in nitrogen fixation and amide utilization by *Azotobacter*: Trans. 3d Internat. Cong. Soil Sci., vol. 1, pp. 152-155.

Byers, H. G., 1935. Selenium occurrence in certain soils of the United States with a discussion of certain related topics: U.S. Dept. Agr. Tech. Bull. 482.

Drobkov, A. A., 1937. The influence of the radioactive elements uranium, radium, thorium and actinium on the yield of plants: Acad. sci. U.R.S.S. Comptes rendus 17, pp. 229-232.

———, 1940. The influence of radioactive elements on the yield of plants: Acad. sci. U.R.S.S. Bull., Biol. Ser., pp. 783-801.

———, 1945. Effect of radioactive elements upon development of root-nodule bacteria and upon the assimilation by them of the molecular nitrogen of the atmosphere: Acad. sci. U.R.S.S. Comptes rendus 49, pp. 224-226.

———, 1951. The part played by natural radioactive elements in biological processes: Uspekhi Sovremennoi Biol., vol. 31, no. 1, pp. 82-100.

Ducloux, E. H., and Cobanera, Maria, 1911-12. The influence of cobalt and vanadium salts on vegetative growth: Rev. Mus. LaPlata, vol. 18, p. 145.

Fischer, Richard P., 1942. Vanadium deposits of Colorado and Utah: U.S. Geol. Survey Bull. 936-P, pp. 363-394.

———, 1950. Uranium-bearing sandstone deposits of the Colorado Plateau: Econ. Geology, vol. 45, pp. 1-12.

Fletcher, M. H., May, Irving, and Anderson, J. W., 1950. The design of the model V transmission fluorimeter: U.S. Geol. Survey, unpublished report.

Free, E. E., and Trelease, S. F., 1917. The effect of certain mineral poisons on young wheat plants in three-salt nutrient solutions: Johns Hopkins Univ. Circ. 293, pp. 199-201.

Gericke, S.. 1941. The effect of vanadium on plant growth: Bodenkunde u. Pflanzenernähr., vol 23, pp. 342-50.

———, and von Rennenkampff, E., 1939. The effect of the trace element vanadium on plant growth: Prakt. Blatter Pflanzenbau Pflanzenschutz, vol. 17, p. 1722.

———, ———, 1940. The effect of vanadium on plant growth: Bodenkunde u. Pflanzenernähr., vol. 18, pp. 305-315.

Gleditsch, E., and Graf, T., 1942. Some effects of radioactive materials on plant growth: Nord. Jordbrforsk, vol. 24, pp. 225-236.

Grimaldi, F. S., Ward, F. N., and Kreher, Ruth, 1950. A direct quantitative fluorimetric method for determining small amounts of uranium in the field and laboratory: U.S. Geol. Survey, unpublished report.

Hoffmann, Josef, 1941. The assimilation of uranium in living fresh water algae: Naturwissenschaften, vol. 29, pp. 403-404.

———, 1942. Detection of uranium in living and dead plants: Bodenkunde u. Pflanzenernähr., vol. 26, pp. 318-327.

———, 1943a. The bio-element uranium in plants, animals, and human organisms: Zeitschr. Biochem., vol. 313, pp. 377-387.

———, 1943b. A further contribution to the distribution of uranium in plant material: Bodenkunde u. Pflanzenernähr., vol. 32, pp. 295-306.

Horner, C. K., and Allison, F. E., 1944. Utilization of fixed nitrogen by *Azotobacter* and influence on nitrogen fixation: Jour. Bacteriology, vol. 47, pp. 1-14.

———, Burk, D., Allison, F. E., and Sherman, M. S., 1942. N-fixation by *Azotobacter* as influenced by molybdenum and vanadium: Jour. Agr. Research, vol. 65, pp. 173-192.

Jacobson, L., and Overstreet, Roy, 1947. The uptake by plants of plutonium and some products of nuclear fission absorbed on soil colloids: U.S. Atomic Energy Commission Document MDDC-1006, 8 pp., declassified.

Kayser, E., 1912. The influence of uranium salts on alcohol fermentation: Acad. sci. Paris Comptes rendus, vol. 155, pp. 246-248.

———, 1921. Influence of uranium salts on nitrogen fixation: Acad. sci. Paris Comptes rendus, vol. 172, no. 18, pp. 1133-1134.

Loew, Oskar, 1902. On the effect of uranium on plants: Tokyo Coll. Agr. Bull., vol. 5, pp. 173-175.

Ramirez, E. C., 1914. Vanadium and its action on plant growth: Am. Soc. Quim. Argentina, vol. 2, no. 6, p. 145.

Robinson, W. O., 1933. Determinaton of selenium in wheat and soils: Jour. Assoc. Offic. Agr. Chemists, vol. 16, pp. 423-424.

———, and Edgington, Glen, 1945. Minor elements in plants, and some accumulator plants: Soil Sci., vol. 60, pp. 15-28.

Stoklasa, Julius, 1913. The influence of uranium and lead on plants: Acad. sci. Paris Comptes rendus, vol. 156, no. 2, pp. 153-155.

Stoklasa, Julius, and Penkava, Joseph, 1928. Biology of uranium: Zeitschr. Biochem., vol. 194, pp. 15-77.

———, ———, 1932. Biology of radium and uranium, Berlin.

Suzuki, S., 1903. On the action of vanadium compounds on plants: Tokyo Bull. Agr., vol. 5, pp. 513-515.

Ter Meulen, H., 1931. On the distribution of molybdenum in nature: Rec. travaux chim., vol. 50, pp. 491-504.

Trelease, S. F., and Beath, O. A., 1949. Selenium, published by authors, New York.

Verducci, Paola, 1945. Comparative effect of radioactivity of uranium compounds on germination and development of seeds: Soc. italiana biol. sper. Boll., vol. 20, pp. 333-334.

Warington, Katherine, 1937. The effect of molybdenum on plants with special reference to the Solanaceae: Ann Applied Biol., vol. 24, pp. 475-493.

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REVIEWS

Silicate Analysis: A Manual for Geologists and Chemists, 2d ed., revised; by A. W. Groves. Pp. xxiii, 336. London and New York, 1951 (George Allen & Unwin, Ltd., and Interscience Publishers, Inc., $5.00).—This revised and considerably expanded (from 230 to 336 pages) edition is highly recommended, not only to chemists, but also to geologists. The chemist will find detailed procedures, including many recent methods, for the separation and determination of major and minor constituents, with valuable suggestions as to techniques. Less usual and highly commendable is Groves' effort to interest and educate the analyst in those mineralogical and geological considerations that help him to decide what elements he ought to determine in a given sample and enable him to check the plausibility and reasonableness of his results. This is done well in chapter 4, part A, "Constituents to be determined in rock analysis," chapter 11, "Occurrences of the various elements," and chapter 12, "Computations as a check on the accuracy of chemical analyses." The geologist will also profit from these chapters, and particularly from chapter 9 on "Errors," where the discussion is, in general, based on knowledge of the analytical processes involved rather than on illusory mathematical juggling of arbitrary formulas. Some of this discussion does appear to be dogmatic, and the statement of limits of error to be expected in analyses seems over optimistic, especially in view of the new results just published in U. S. Geological Survey Bulletin 980.

Some differences in opinion may be expected among analysts as to some procedures. The reviewer disagrees with Groves' recommendation of the determination of F gravimetrically as CaF_2 or colorimetrically by the Steiger-Merwin method. The Willard-Winter method is given only in connection with the analysis of phosphates, and then not in the form most widely used in this country. Groves points out in some detail the faults of the conventional Penfield method for the determination of water, and recommends heating in a silica tube at 1000°. However, nothing is said of the Penfield method with fluxes such as Na_2WO_4 or PbO, even though it is stated that fluxes must sometimes be used in the silica-tube method.

Throughout the book the word lime is used, not only for CaO, but also for calcium, as in "Lime is precipitated as the oxalate," and the words magnesia, alumina, etc., are similarly misused. It is to be hoped that such usage will be discontinued along with the usage of soda for Na_2O and potash for K_2O. Although structural formulas are clearly explained and illustrated in chapter 12, the mineral formulas used elsewhere (as on p. 267) are unsatisfactory and some are erroneous. MICHAEL FLEISCHER

Type Invertebrate Fossils of North America (Devonian), Di i-sion I, Unit 1-F. Tetracoralla, Part A; by ERWIN C. STUMM. Philadelphia, 1951 (Wagner Free Institute of Science).—Having completed a revision of the tabulate corals of the Devonian, Dr. Stumm now presents the first unit of the tetracorals—88 cards covering 60 species representing 12 genera and 4 families.

The nomenclatorial confusion that has frustrated students of Devonian corals is probably without a parallel in American paleontology. It began in 1885 with the almost simultaneous appearance of two large works on the prolific coral faunas at the Falls of the Ohio near Louisville. James Hall named and briefly described 135 new species of which 97 were not illustrated (N. Y. State Mus., 35th Ann. Rept., 1885). William J. Davis named and illustrated 312 new species from the same area but the projected volume of text was never published (Kentucky Fossil Corals, Pt. 2, Plates. Geological Survey of Kentucky, 1885). G. K. Greene later confounded the confusion by completely disregarding the works of both Davis and Hall and naming and briefly describing 181 "new" species of corals from the Falls of the Ohio (Contributions to Indiana Paleontology, 1898-1906). Thus some 600 species of fossil corals were named from a single small area, by three men working independently. Almost 100 were based upon description without illustrations, over 300 on illustrations without description, and nearly all of them were based on external features alone.

Dr. Stumm's competent study of the types of Devonian corals should clean out the Augean stables. This first contribution is most welcome and subsequent units will be eagerly awaited.

CARL O. DUNBAR

Soil Survey Manual; by SOIL SURVEY STAFF. U. S. Department of Agriculture, Handbook Number 18. Pp. vii, 503; 11 plates, 60 figs., 13 tables, 5 appendices. Bureau of Plant Industry, Soils, and Agricultural Engineering, Washington, 1951 (Government Printing Office, $3.00).—This publication, "intended for use by soil scientists engaged in soil classification and mapping" (p. v) represents a complete revision of an earlier *Manual* (USDA, Miscellaneous Publication 274, 1937). The first part of the present *Manual* is devoted to methods for collection, assembly, and interpretation of field data and includes several chapters on the physical characteristics of soils. Mapping methods based on the use of aerial photographs are emphasized throughout the Handbook, and three two-part plates illustrating field maps drawn on photographs are particularly valuable. The second half of the *Manual* is devoted to the actual classification, correlation, and mapping of soils in addition to the pertinent edaphologic applications of soil science

principles. Older methods for the preparation of soil maps, such as the use of the plane table, are relegated to the appendices which also include sample descriptions of soil series and notes on map compilation and reproduction.

The modifications, aimed to achieve more quantitative and uniform results in the organization of field data, are commendable. The addition of sections on parent materials of soils and the relationship between soils and geomorphic features is indicative of the increasing awareness by soil scientists of the importance of genesis, as well as morphology, to soil classification.

The authors trace the evolution of soil science from the early surveys where "soils were conceived to be the weathering products of recognized geological formations, defined by landform and lithological composition" (p. 2) to the modern concept of "soils as dynamic three-dimensional landscapes" (p. 5). Marbut's emphasis on morphology as the sole basis for classification and his deliberate neglect of genetic relationships are, in the opinion of the reviewer, intelligently discarded. However, a knowledge of soil genesis on the part of the reader is presupposed and there is no integrated section on genetic principles. From the viewpoint of the geologist this is, perhaps, the most serious limitation to the usefulness of the *Manual.*

Although the authors emphasize the need for adherence to the correct use of geologic terminology, they have themselves not been entirely successful in the application of geologic terms to soil science. Inclusion of unconsolidated sediments (e.g., marl, sand, silt, clay, and gravel) under the ambiguous classification "soft rocks" (p. 149) is a case in point. Accepted use of the term "horizon" in a three-dimensional sense by soil scientists (p. 173) in contrast to the two-dimensional concept now favored by geologists is another reminder that geology and soil science are still far from attaining a common terminology which is both consistent and uniform. There is indeed still a critical need for closer cooperation between workers in soil science and geology in order to expand our knowledge of the origin of soils. JULES D. FRIEDMAN

Manual of Phycology, An Introduction to the Algae and their Biology. Edited by GILBERT M. SMITH. Pp. xi, 375; 48 figs. Waltham, Mass., and New York, 1951 (Chronica Botanica Company, and Stechert-Hafner, Inc., $7.50).—These remarks are not designed to be read by phycologists—who, even if they have not personally expended $7.50, will certainly by now have located a copy of "Manual of Phycology" within easy borrowing range—but rather are they addressed to the lay botanist. To him, Smith's "Manual" may be introduced as a bible of phycology, consisting of 19 'books'

by almost as many men, who, though differing considerably in their philosophies of approach to their several subjects, and whose accounts occasionally conflict in small points of detail, must nevertheless be regarded as prophets or apostles of almost unquestionable authority.

The volume is divisible into two parts of equal length: an Old Testament, dealing with the classical aspects of phycology—what the algae are like—and a New, comprising revelations on the (to me) redeeming features of the subject—what we can do with them.

In the beginning, Prescott reviews the history of phycology; the editor follows with an outline of algal classification; and we then embark on a phylum-by-phylum treatment of morphology, anatomy, and life-cycles. The Chrysophyta are the only group on which Fritsch has contributed directly; but the hand of the master is apparent elsewhere, too, and the tasks of Iyengar, Papenfuss, Drouet and Drew in preparing their chapters on the Greens, the Browns, the Blue-greens and the Reds, and that of Graham in his review of the Pyrrophyta, must have been considerably lightened by having Fritsch's "Structure and Reproduction" at their elbow. Jahn, in the bibliography to his discussion of the Euglenophyta, admits of no such assistance—but I suspect him notwithstanding. A brief account of palaeophycology by Harlan Johnson concludes the first part.

In the second, Johansen and Bold offer chapters on microtechnique and cytology, and Pringsheim a synopsis of his own volume on culture methods. The ecologies of freshwater and marine algae, and the special topic of plankton, are discussed with a refreshing diversity of perspective by Tiffany, Feldmann, and Ketchum. Blinks has been constrained, alas, to squeeze into 20 brief pages most of algal physiology and biochemistry, but the pigments have been left to Strain. (A projected chapter on economic phycology "did not materialise": a special section on the protean field of algal photosynthesis was—probably very wisely—omitted.) And so, with Smith's survey of sexuality, including some of his own recent observations on *Chlamydomonas*, we conclude the chapter analysis. A final word must be put in for the index, which, if not a concordance, is at least reasonably complete.

As behooves the publishers of any volume which will receive as much hard use as Smith's "Manual," Chronica Botanica have seen to it that the binding is solid. Why they should have chosen to print certain sections—notably on the Chrysophyta and Phaeophyta—on brownish paper, I have been unable to discover. But they must be allowed publishers' license, for they have brought out an excellent work. Professor Smith, in collecting and editing such valuable con-

tributions from the corners of the earth, is to be especially congratulated, and you too, lay botanist, will learn to thank him.

RALPH A. LEWIN

Insect Natural History; by A. D. Imms. Pp. xviii, 317; 39 colored plates, 32 half-tone plates, 40 figs., 8 maps. Philadelphia, 1951 (The Blakiston Co., $5.00).—This is an American issue of a book published in Britain in 1947. It is a volume of the New Naturalist series, published by Collins, of London. The series is probably unsurpassed anywhere in its combination of scientific accuracy, pleasant readability, and superb illustrations. This book is written for the general reader of natural history literature, but, unlike many recent works so directed, this one is factually correct and has balanced breadth which makes it also a useful summary for biologists. It will serve well as a reference for assigned reading for college students of entomology, natural history or general biology. As aspects of Natural History, Imms includes structure, classification, locomotion and senses, feeding habits, reproduction and development, environmental adaptations, and sociology. He also devotes a chapter to Biological Control, an effective approach to pest insects long endorsed by British entomology.

The late author also wrote the finest general textbook in the English language for entomological specialists, and it is satisfying to find his style of writing so comfortable in this new book for the general reader. Many of the half-tone photographs are excellent, but it is the colored plates which take the eye. The 99 color-photographs of living insects are near perfection and serve to vitalize the text to a remarkable degree.

Although very few of the actual species mentioned and figured may be found in North America, close relatives of nearly all occur here. Thus, the book does not have an exotic aspect for us.

There are errors, but they are few and minor. For example: there are said to be 12 British species of Thysanura, though half that number would be more accurate; the "Diplura" are characterized as having "two very long tail filaments," although two of the three families cannot be so described; and the student of the density of Collembola in meadow soil was J. Ford, not "E. B. Ford." One wonders why Imms, without qualification, refers to the Collembola as insects, when his own research papers showed most persuasively that they are not true insects. One point in the make-up of the book is confusing: the black-and-white and colored plates are intermingled through the book, but the black-and-white plates are numbered independently of the colored plates, making it at first distracting to try to look up text references.

CHARLES L. REMINGTON

PUBLICATIONS RECENTLY RECEIVED

Basic Theories of Physics: Heat and Quanta; by P. G. Bergmann. New York, 1951 (Prentice-Hall, Inc., $6.70).

The Aurorae; by L. Harang. New York, 1951 (John Wiley & Sons, Inc., $4.50).

Annual Reports on the Progress of Chemistry for 1950, Vol. 47. London, 1951 (The Chemical Society, $3.50).

Annual Reports on the Progress of Chemistry, Cumulative Index, Vols. 1-46 (1904-1949). London, 1951 (The Chemical Society, $3.50).

High Frequency Transmission Lines; by Willis Jackson. Methuen's Monographs on Physical Subjects. New York and London, 1951 (John Wiley & Sons, Inc., and Methuen & Co., Ltd., $1.75).

Quantum Theory of Matter; by J. C. Slater. New York, 1951 (McGraw-Hill Book Company, $7.50).

Crystal Structures, Vol. II and First Supplement to Vol. I; by R. W. G. Wyckoff. New York, 1951 (Interscience Publishers, Inc., Vol. II, $10.00; Supplement, $4.00).

Geology and Ground-water Resources of Lane County, Kansas; by G. C. Prescott, Jr. Kansas Geological Survey Bulletin 93. Lawrence, 1951 (University of Kansas).

Ground Water Investigations Along Bogue Phalia Between Symonds and Malvina, Bolivar County; by T. W. Lusk. Mississippi Geological Survey Bulletin 72. University, 1951.

Further Studies of Ohio Coals and Oil Shales. Part I, Some Studies of Ohio Coals and Oil Shales; by P. O. Krumin. Part II, Ohio Coals; by W. H. Smith. Part III, Ohio Shales and Cannel Coals; by C. H. Bowen. Ohio State University Engineering Experiment Station Bulletin 143. Columbus, 1951 (Ohio State University, $1.00).

Studies of Compressive Stress Distribution in Simply Reinforced Concrete Near the Point of Failure; by L. A. Herr and L. E. Vandegrift. Ohio State University Engineering Experiment Station Bulletin 1944. Columbus, 1951 (Ohio State University, $.50).

Equivalent Circuits of Electric Machinery; by Gabriel Kron. New York, 1951 (John Wiley & Sons, Inc., $10.00).

Oil and Gas Developments in Kansas during 1950; by W. A. ver Wiebe *et al.* Kansas Geological Survey Bulletin 92. Lawrence, 1951 (University of Kansas).

Spinoza Dictionary; D. D. Runes, Editor. New York, 1951 (Philosophical Library, $5.00).

The Philosophy of the Enlightenment; by Ernst Cassirer. Princeton N. J., 1951 (Princeton University Press, $6.00).

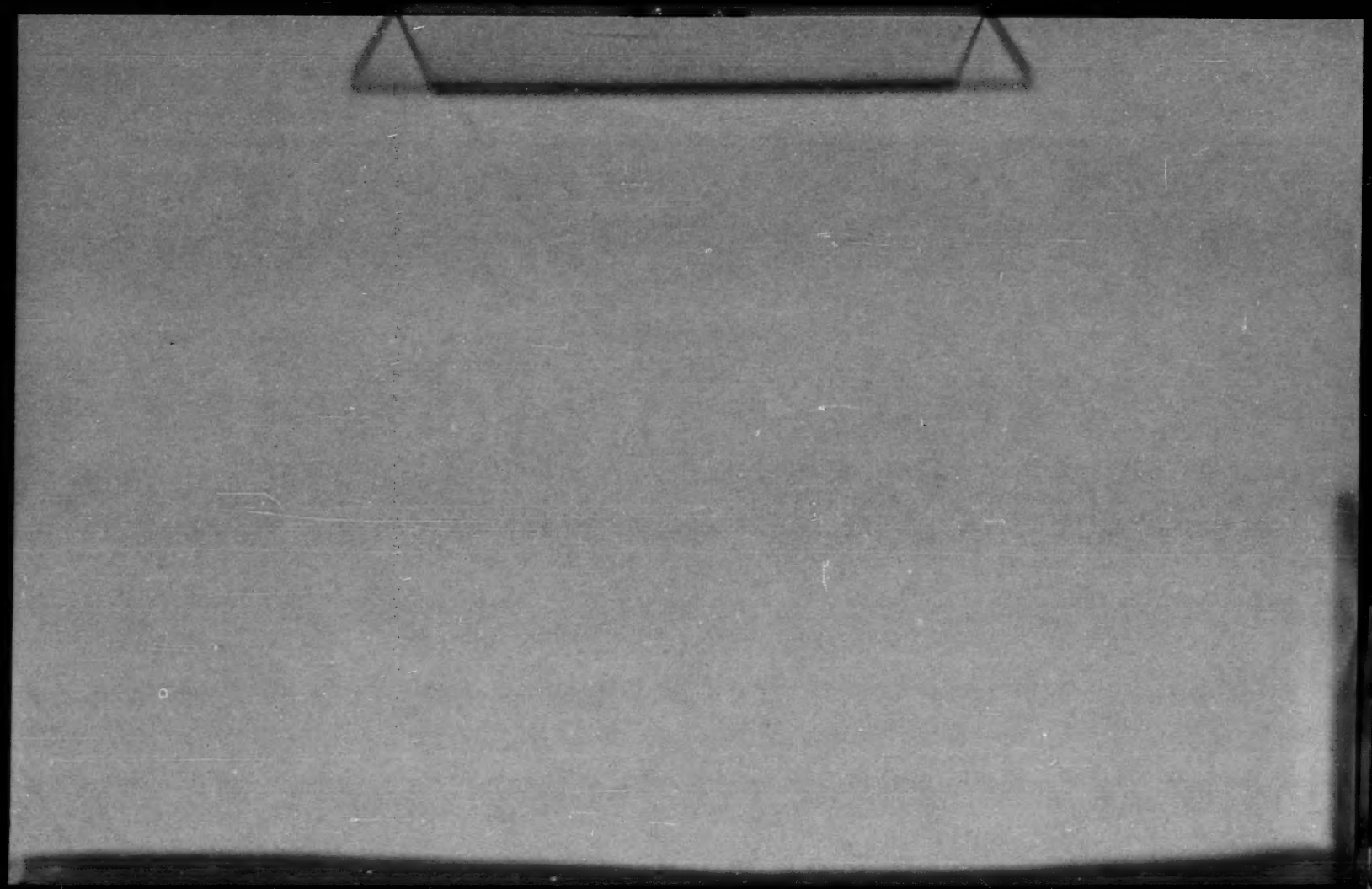
An Approach to Design; by N. T. Newton. Cambridge, Mass. (Addison-Wesley Press, Inc., $3.50).

Helicopter Analysis; by A. A. Nikolsky. New York and London, 1951 (John Wiley & Sons, Inc., and Chapman & Hall, Ltd., $7.50).

Tensor Analysis, Theory and Applications; by I. S. Sokolnikoff. New York and London, 1951 (John Wiley & Sons, Inc., and Chapman & Hall, Ltd., $6.00).

Lafayette County Geology; by James S. Attaya. Mississippi State Geological Survey Bull. 71, University, 1951.

The Occurrence of Columbite in Nigeria; by R. R. E. Jacobson, A. Cawley and W. N. MacLeod. Geol. Survey of Nigeria Occasional Paper 9. Nigeria, 1951 (1s, 6d).



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Payne & Lane, *Printers* — New Haven, Conn.